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Field site radar systems

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ALBERTA RESEARCH COUNCIL

Natural Resources Division
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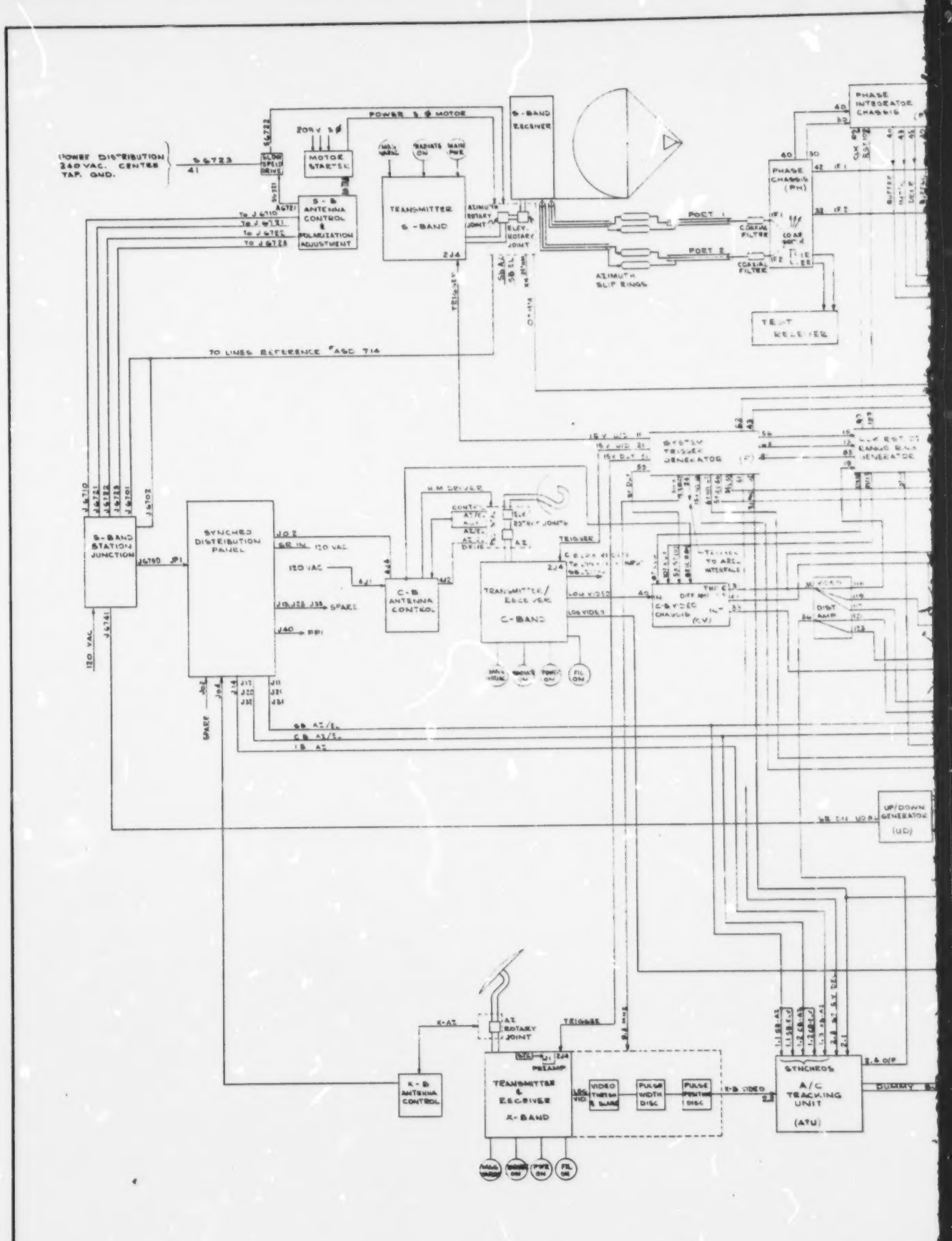
Preface

The purpose of this manual is to aid assistants in becoming familiar with the Alberta Research Council, Atmospheric Sciences Department radar systems. The electronic systems are constantly evolving, therefore this manual has provision for numerous updates.

This manual is presented in four chapters. Chapter one, "Fundamentals of Radar" is an introduction to radar. It is edited from a draft manuscript written by Dr. P.L. Smith. Chapter two provides a general description of the project radars and associated systems. Chapter three deals with operations of the systems. Chapter four deals with system calibration and operational checks.

There are five Appendices. Appendix A provides detailed description and operation of selected electronic systems. Appendix B provides theory of selected topics. Appendix C contains a list of abbreviations, appendix D is a glossary of terms and appendix E contains calibration and operational check sheets.


POWER 3 Ø MOTOR
S-BAND ESCRIVER
PHASE INTEGRATOR CHASSIS
POWER DISTRIBUTION 240 VAC. CENTER TAP. GND.
MOTOR STARTER
S-B ANTENNA CONTROL & POLARIZATION ADJUSTMENT
TRANSMITTER S-BAND
PHASE CHASSIS (PH)
AZIMUTH ROTARY JOINT
ELEV. ROTARY JOINT
PORT 1
PORT 2
COAXIAL FILTER
AZIMUTH SLIP RINGS
TEST RECEIVER
70 LINES REFERENCE AGC 714
SYSTEM TRIGGER GENERATOR
RANGE SYNC GENERATOR
H.M. DRIVER
S-BAND STATION JUNCTION
SYNCHRO DISTRIBUTION PANEL
120 VAC
C-B ANTENNA CONTROL
TRANSMITTER/ RECEIVER C-BAND
TRIGGER
TO ARC INTERFACE
C-B VIDEO CHASSIS (CV)
DIST AMP
SPARE
PPI
UP/DOWN GENERATOR (UD)
X-AZ
AZ ROTARY JOINT
TRIGGER
PREAMP
X-B ANTENNA CONTROL
TRANSMITTER & RECEIVER X-BAND
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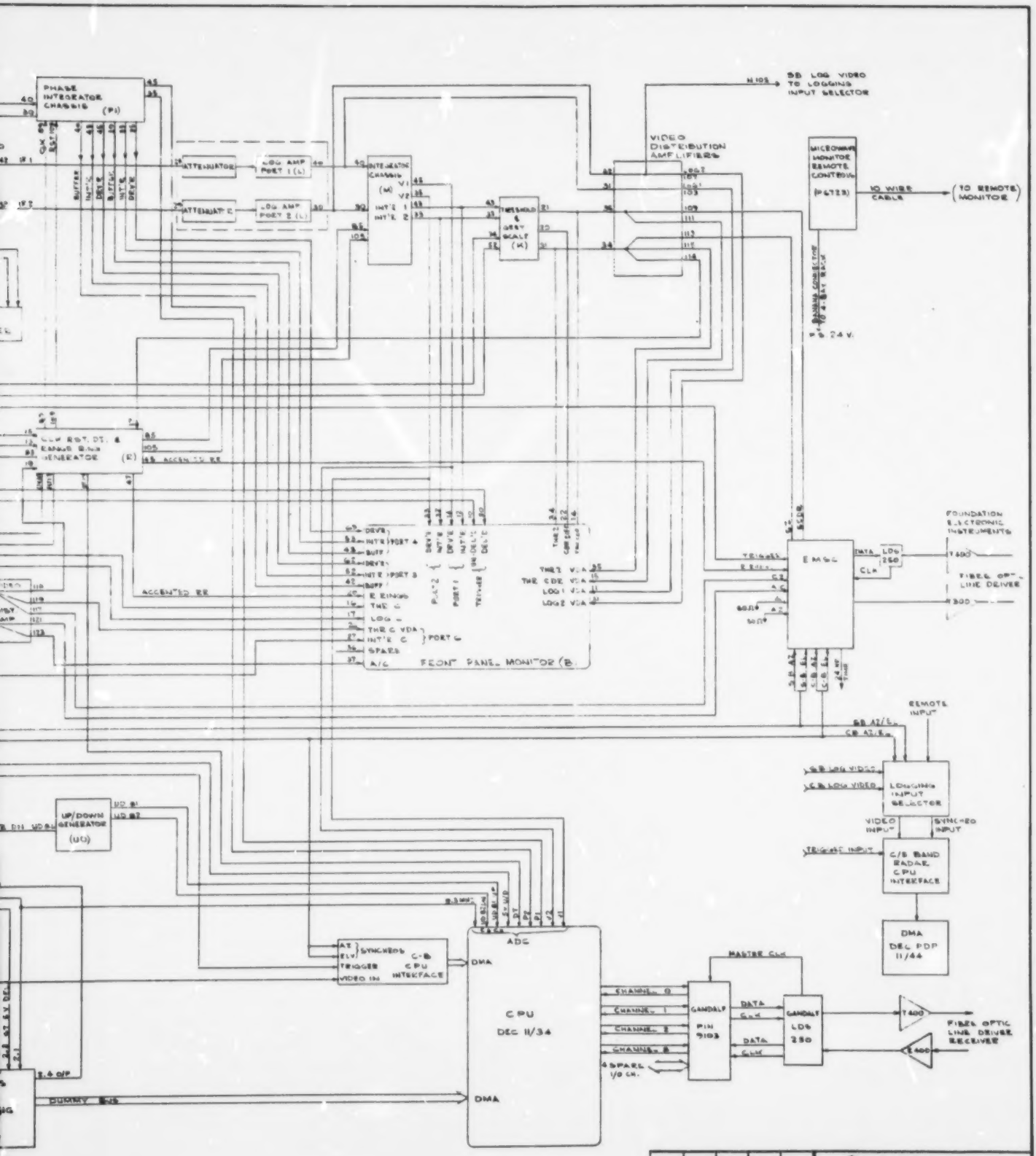
SYNCHROS
A/C TRACKING UNIT (ATU)
DUMMY


PHASE INTEGRATOR CHASSIS (P1)
ATTENUATOR
LOG AMP PORT 1 (L)
ATTENUATOR
LOG AMP PORT 2 (L)
INTEGRATOR CHASSIS (M)
INT'E 1
INT'E 2
THRESHOLD & GREY SCALE (M)
VIDEO DISTRIBUTION AMPLIFIERS
N105
SB LOG VIDEO TO LOGGING INPUT SELECTOR
MICROWAVE MONITOR REMOTE CONTROL (P6723)
10 WIRE CABLE
TO REMOTE MONITOR
+ 24 V.
CLK ROT. DT. & RANGE RING GENERATOR (R)
ACCENTED RR
FRONT PANEL MONITOR (B)
EMGC
FOUNDATION ELECTRONIC INSTRUMENTS
FIBRE OPTIC LINE DRIVER
REMOTE INPUT
LOGGING INPUT SELECTOR
VIDEO INPUT
SYNCHRO INPUT
C/B BAND RADAR CPU INTERFACE
DMA DEC PDP 11/44
UP/DOWN GENERATOR (UG)
ADC
SYNCHRO C-B CPU INTERFACE
CPU DEC 11/34
DMA
MASTER CLK
CHANNEL 0
CHANNEL 1
CHANNEL 2
CHANNEL 3
4 SPARE I/O CH.
GANDALF PIN 9103
GANDALF LDS 250
FIBRE OPTIC LINE DRIVER RECEIVER
Alberta RESEARCH COUNCIL
RED DEER - AIRPORT
RADAR SYSTEMS FUNCTIONAL BLOCK DIAGRAM
N.T.S.

Chapter one: Fundamentals of radar

Introduction

Radar is an acronym derived from Radio Detection And Ranging. The early development of radar was stimulated by the necessity to detect approaching hostile aircraft during World War II.

Most radars operate within the microwave portion of the electromagnetic spectrum, with many notable exceptions. A radar system emits electromagnetic radiation then detects reflected radiation from objects illuminated in the path of the emitted radiation. Since radar systems illuminate objects with their own transmissions, they can be used equally well night or day. Low frequency radars such as L-Band (1-2 GHz), S-Band (2-4 GHz) and C-Band (4-8 GHz) penetrate haze, fog and snow readily; and hail somewhat less readily. Higher frequency radars, in the X-Band (8-12.4 GHz) through K-Band (12.4-40 GHz) range, are seriously hampered by these environmental conditions. The atmospheric attenuation or "loss" increases as the microwave frequency increases. The radar's characteristics and its ability to penetrate atmospheric medium provide an invaluable tool for meteorological research.

Table 1.1. JCS band designation

VHF Band	100	MHz	to	300	MHz
UHF Band	300	MHz	to	1	GHz
L Band	1	GHz	to	2	GHz
S Band	2	GHz	to	4	GHz
C Band	4	GHz	to	8	GHz
X Band	8	GHz	to	12.4	GHz
Ku Band	12.4	GHz	to	18	GHz
K Band	18	GHz	to	26	GHz
Ka Band	26	GHz	to	40	GHz
millimetre	40	GHz	to	100	GHz

Operation overview

A radar system operates by sending out electromagnetic signals and picking up the electromagnetic energy scattered back by objects in the environment. The objects are usually referred to as targets, regardless of their actual nature. Most objects scatter microwaves to some degree and the scattered signals received from the targets are referred to as echoes.

An elementary radar system is depicted in figure 1.1. The transmitter's microwave output is focused into a narrow beam by an antenna. The emitted wave strikes the target and a portion of it is then scattered back toward the radar. The echo is collected by another antenna and passed on to the receiver. This signal is then processed to extract target data and displayed to the user of the radar system. The angle coordinates, azimuth and elevation, of the target are found from the direction that the antenna is pointed. Radar is capable of measuring the distance to the target and thus gives the target position in three dimensions. For a fourth dimension, the Radial Velocity can be detected as a frequency shift, known as the doppler shift, of the echo frequency from that of the transmitted frequency.

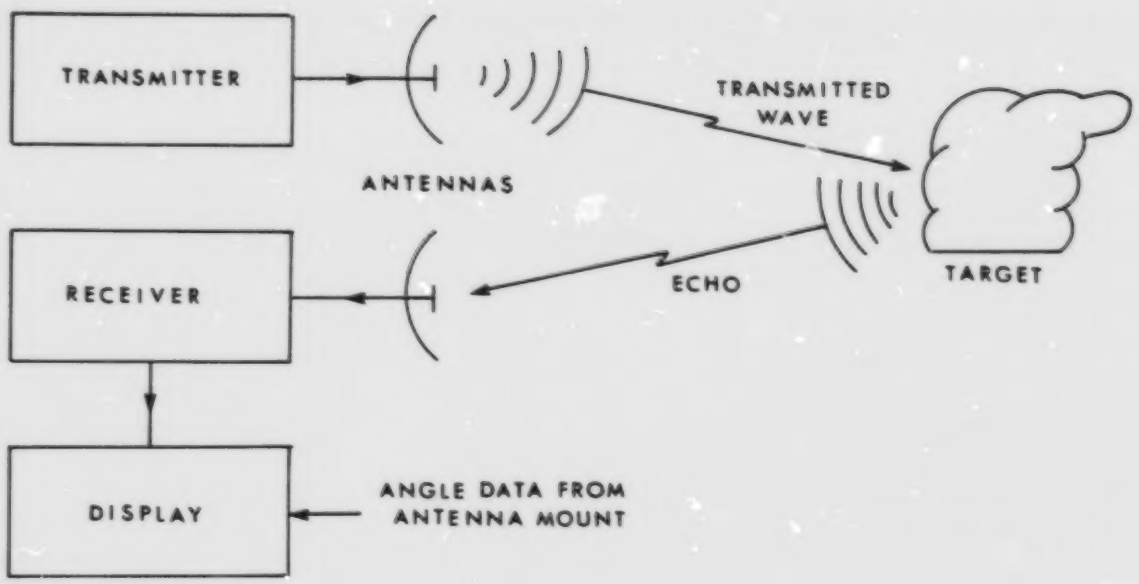


Figure 1.1. An elementary radar system

The distance, or range to the target is determined by measuring the time interval between transmission of the signal and reception of the echo. The velocity of propagation "c", of microwaves in the atmosphere,is 3×10^{-8} m/s. For a target at range "r", the signal must travel out to the target and back, a total distance of 2r. If the time interval between transmission of the signal and reception of the echo is Δt seconds, then $\Delta t = 2r/c$. For targets of interest in radar meteorology, this time interval will range from a few microseconds to a few milliseconds. If the interval Δt is measured, the range to the target is found from $r = c \Delta t/2$.

Some useful numerical values derived from the above equations are listed in Table 1.1.

Target Range "r"		**Round-Trip Transit Time "t"**
1	kilometre	6.67 microseconds
1	statute mile	10.75 microseconds
1	nautical mile	12.36 microseconds
1000	yards	6.1 microseconds
0.081	nautical mile	1.0 microseconds
150	metres	1.0 microseconds

The block diagram of a typical pulsed radar system is shown in figure 1.2. This diagram shows the components of such a radar; it is more complex than the elementary radar of figure 1.1, but the components can still be grouped into the main functional elements: transmitter, antenna, receiver and display. One important difference between the elementary system of figure 1.1 and the system of figure 1.2 is that the latter uses the same antenna for both transmitting and receiving. This is accomplished by introducing a fast-acting switch called a duplexer which alternately connects the antenna to the transmitter and receiver.

A pulsed radar system transmits microwave signals in short bursts, or pulses. The duration of these pulses is often only a few microseconds and occur at a rate of several hundred per second. The operation of the radar system in figure 1.2 is controlled by the timer. This device generates a series of timing (trigger) pulses at a rate called the "pulse repetition frequency" (PRF) of the radar. Each of these pulses sets the display circuits to their starting condition and causes the transmitter to transmit a pulse of RF energy. The trigger pulse causes the modulator inside the transmitter to deliver a pulse of high voltage and power to the transmitter's microwave tube. The width of the modulator pulse determines the transmitted pulse width, the design of the microwave tube determines the frequency of the transmitted pulse.

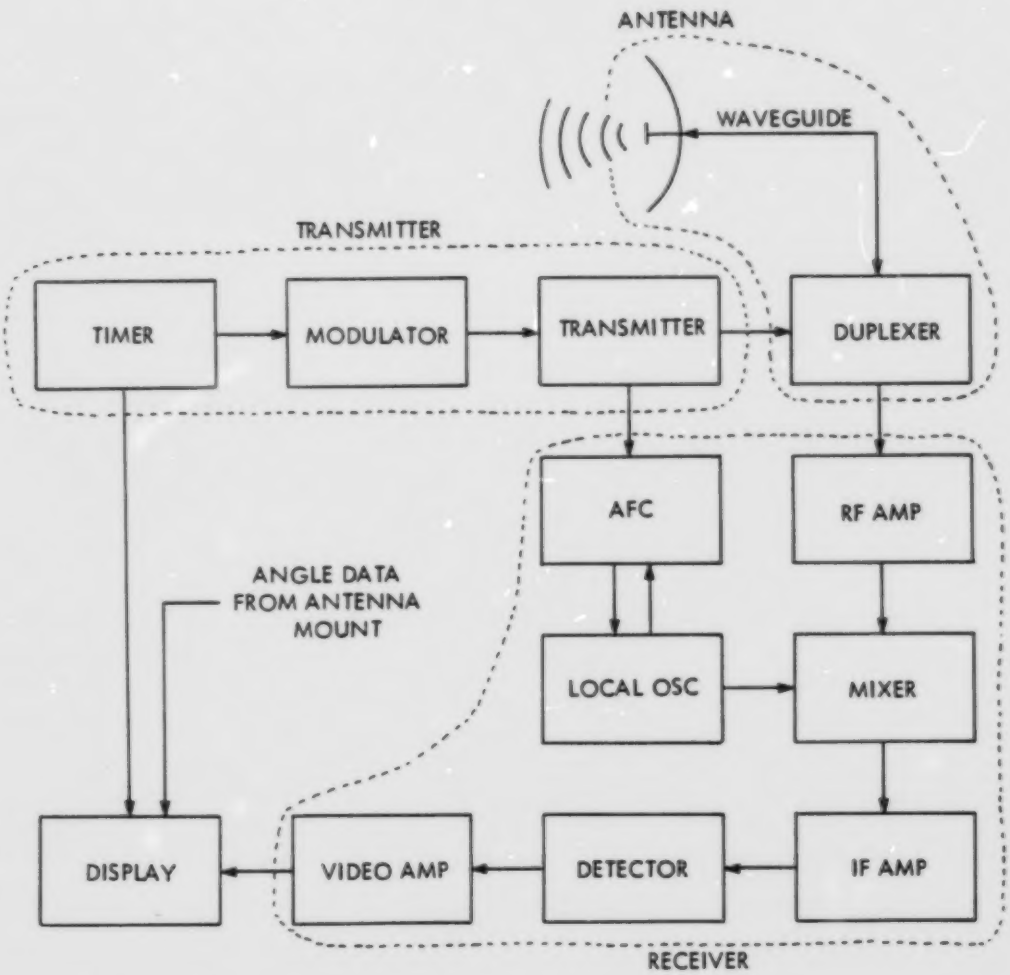


Figure 1.2. Simplified block diagram of a pulsed radar

These RF pulses travel through a waveguide and through the duplexer to the antenna.

The duplexer actually comprises two separate switches as shown in figure 1.3. Both switches are usually gas-discharge tubes, in which the discharge is started by and maintained by the RF pulse from the transmitter. The switch closer to the transmitter is the Anti-Transmit-Receive (ATR) switch. The switch nearer the antenna is the Transmit-Receive (TR) switch. The TR disconnects the receiver during the transmitter pulse, protecting the receiver from being damaged during the high-power pulse while the ATR switch allows the transmitter pulse to pass to the antenna. During the listening period, the TR switch connects the receiver to the antenna and the ATR switch disconnects the transmitter by presenting a high impedance and reflecting the return signal to the receiver.

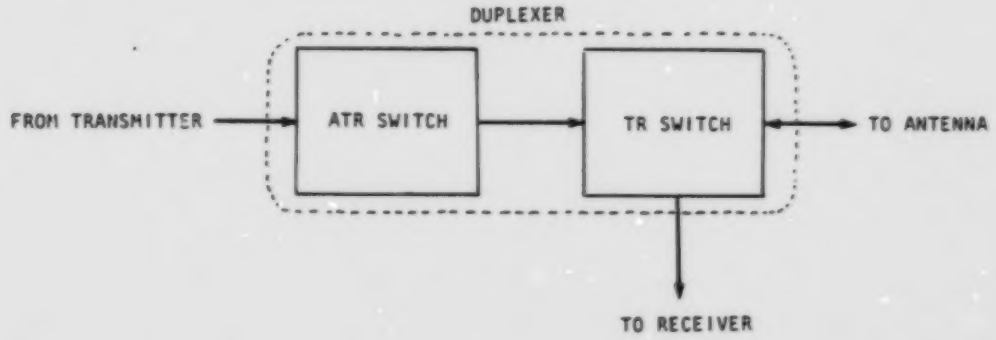


Figure 1.3. A radar duplexer

The antenna is designed to focus the microwave radiation into a beam of appropriate shape for its particular application. In weather radars the beam is usually in the form of a narrow cone called a pencil beam.

The radar echoes received by the antenna travel through a wave guide, to the duplexer, and then to the receiver. Radar receivers are usually of the super heterodyne type as shown in figure 1.3. The first stage of the receiver, referred to as the front end, would consist of a mixer and/or an RF amplifier. The mixer is a nonlinear device, usually one or more crystal diodes, which convert the RF echo to a lower frequency called the intermediate frequency (IF). The process of converting to another frequency is called heterodyning. The IF outputof the mixer contains exactly the same information (in both amplitude and phase) as did the incoming RF signal. The conversion from RF to IF is performed because IF frequencies are easier to handle and IF devices are much less expensive than corresponding RF devices.

To accomplish the conversion to the IF, the mixer must be supplied with a continuous wave (CW) low power (milliwatts) signal source called the local oscillator (LO). The LO operates at a frequency a few tens of megacycles away from the transmitted frequency. The frequency difference between the transmitter and LO corresponds to the IF frequency of the receiver. IF stages of the receiver are designed to operate at a fixed frequency, therefore the difference between the transmitter and LO frequencies must be maintained at a constant value. In radars employing magnetrons as transmitters, this is often accomplished by an automatic frequency control circuit (AFC). The AFC is a electronic servomechanism that continually adjusts the LO frequency to maintain the proper IF. It does this by sampling the transmitted pulse and comparing its frequency with that of the LO. If the frequency difference is not equal to the desired IF, the AFC adjusts the LO to obtain the correct IF.

The output of the mixer is amplified in a linear amplifier or logarithmic amplifier to a suitable level for subsequent use. The output signal of the IF amplifier is a modulated sine wave that must be submitted for either synchronous or envelope detection techniques to obtain the desired video signal for display. This is done in the detector.

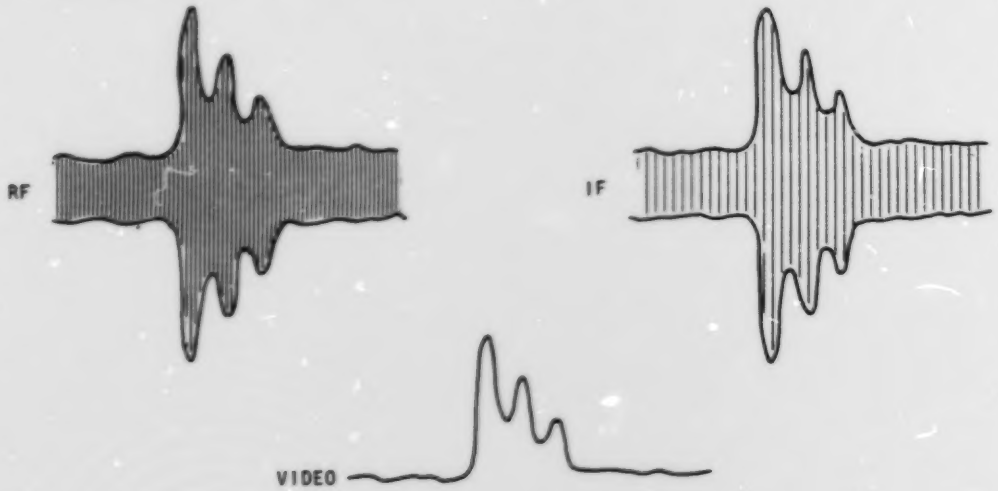


Figure 1.4. Demodulation of an IF signal

In the detector, the IF signals are demodulated and only the modulation envelope remains (figure 1.4). The output of the detector contains the amplitude information (but not the phase) of the original RF echo. The detector output called the "video" signal, is amplified to a level suitable for driving a display.

There are many types of radar displays in use today but for the present let us assume that the display comprises of a cathode-ray tube (CRT) operated in the manner of an ordinary oscilloscope (see section 2.2.2.1). The horizontal axis is a time-based sweep, started synchronously with the system trigger. The vertical axis represents the video amplitude.

The display shows the video output of the receiver as a function of time, starting from the time of the trigger pulse. A linear display of this type is known as an "A-scope" (figure 1.5). The range to the target can be found by measuring the time interval between the transmitted pulse (main bang) and the echo, then inserting it into the equation $r = c\ T/2$. The position of the target, in three dimensions, can be found from this calculated range and the angle coordinates from the antenna mount.

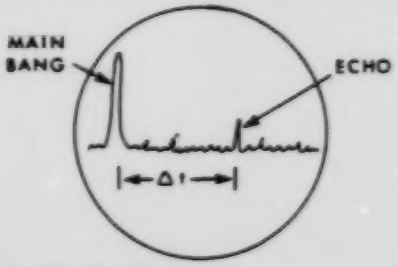


Figure 1.5. An A-Scope display

Another commonly used display is the plan position indicator (PPI).This display produces a map-like display as shown in figure 1.6. The radar antenna azimuth is presented as an angular displacement from the top of the screen and the range as a radial distance from the center of the screen to the echo image. The origin of the display represents the radar antenna. The height of the target can be calculated from the antenna elevation and target range.

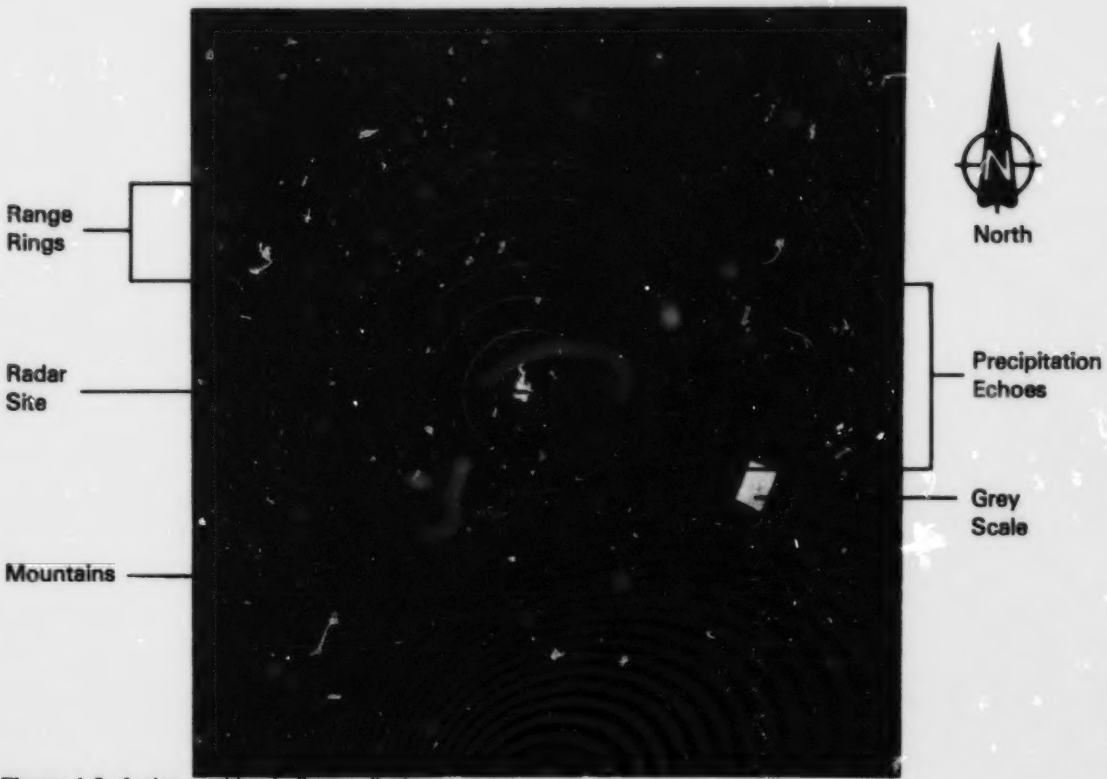


Figure 1.6. A plan position indicator display

There are many components of a radar system that have not been shown in the basic block diagram (figure 1.2). A few of the more important ones are:

1. Automatic gain control (AGC) circuits, used to control the gain of the IF amplifier to prevent saturation of the receiver by strong echoes.

2. Directional couplers, inserted in the waveguide between the duplexer and the antenna to sample the transmitter output and inject test signals into the receiver.

3. Servosystems, used to position the antenna in azimuth and elevation.

4. Selsyns (synchros) or resolvers to measure the coordinates to which the antenna is pointed.

5. Power supplies, used to supply the voltage and currents required by the various parts of the radar system.

Chapter two: General descriptions

2.1 Introduction to electronic systems

Over the years the project radars have evolved into many complex systems and subsystems. They are:

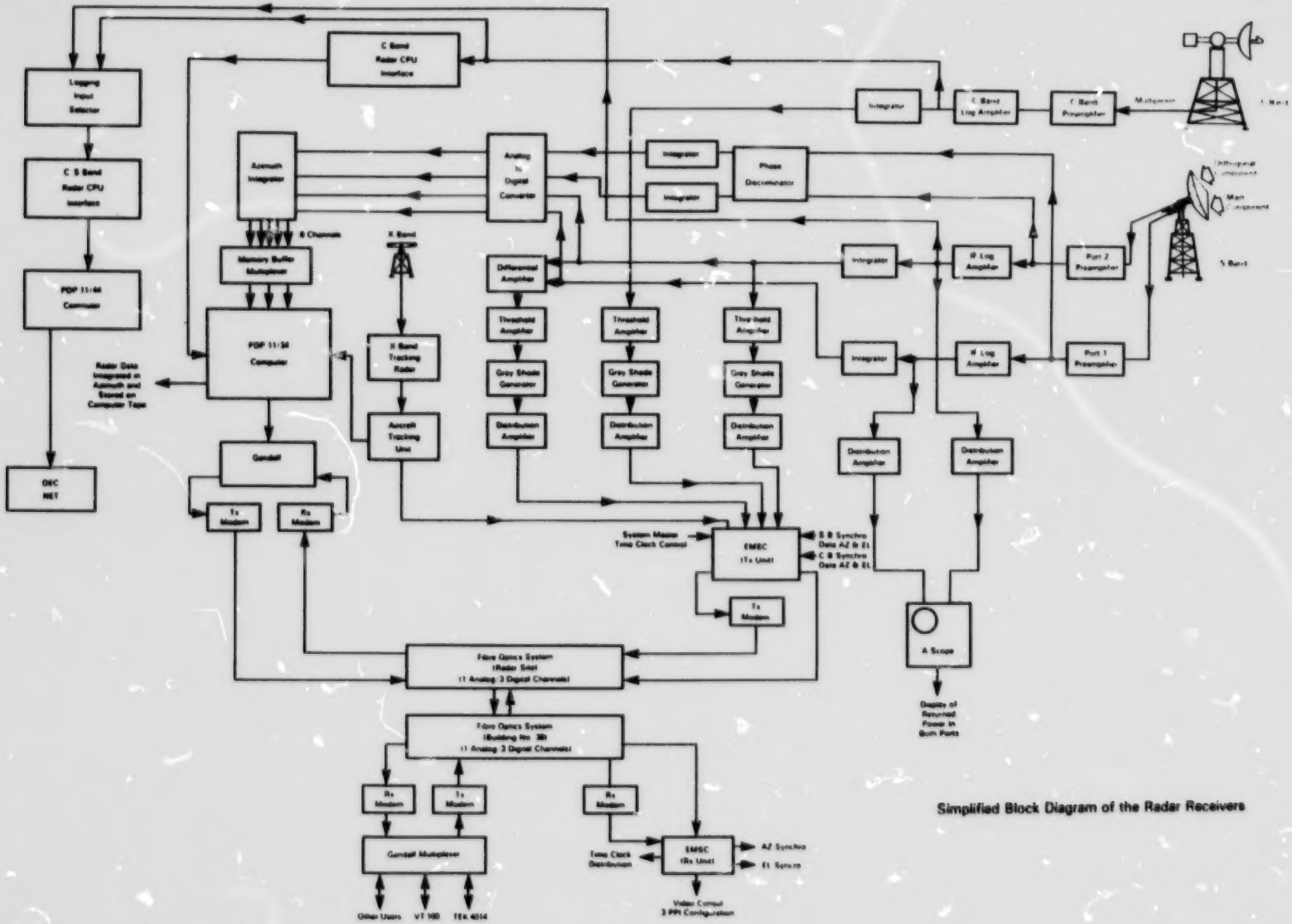
- S-Band meteorological radar
- C-Band meteorological radar
- X-Band aircraft tracking radar
- Aircraft Tracking Unit
- Computers
- Computer Interfaces
- Fibre Optic Transmission System
- Plan Position Indicators
- Range Ring Generator
- Remote Data Transmission System
- S-Band Monitor
- Standby Power Generator
- Statistical Multiplexers
- System Trigger Generator
- Test Receiver
- Video Distribution Amplifiers

2.1.1 Radar Systems

2.1.1.1 C-Band

The C-Band radar is the primary surveillance and secondary operational radar. The characteristics of the C-Band radar are as follows:

frequency	5.635	GigaHertz
pulse repetition frequency	478	Hertz
Pulse duration	2	microsecond
typical peak power	200	kiloWatt
polarization	horizontal	
beam width	1.5	degrees in all planes
antenna gain	40	dB
azimuth rotation rate	8	rpm maximum
elevation program	step scan: 1.5 degrees per azimuth rotation, 0 to 9 degrees 0 to 21 degrees	



Simplified Block Diagram of the Radar Receivers

Figure 2.1. Simplified block diagram of the radar systems

2.1.1.2 S-Band

The S-Band radar is used as the prime operational radar for all experiments.

The characteristics of the S-Band radar are as follows:

frequency	2.880	GigaHertz
pulse repetition frequency	478	Hertz
pulse duration	1.0	microsecond
typical peak power	400	kiloWatt
polarization	variable: LHC, RHC, or LINEAR	
axial orientation	variable: any	
beam width	1.15	degree
antenna gain	43.2	dB (at pedestal)
azimuth rotation rate	8	rpm normal,
	0.75	rpm max slow
elevation program		spiral scan: 1 degree per azimuth rotation, 0 to 8 degrees or 0 to 20 degrees

The S-Band is equipped with a variable polarization antenna and dual channel receiver. The antenna is capable of transmitting elliptically polarized radiation at any chosen axial ratio or orientation. The antenna is normally set to transmit with left hand circular polarization. The received radiation is resolved by the antenna microwave circuits into its main and orthogonal components (port 2 and port 1). These components enter separate receiving channels for processing as reflectivity and circular depolarization ratio (CDR) video data. Refer to appendix A for detailed theory of the S-Band antenna.

2.1.1.3 X-Band

The X-Band radar is an aircraft tracking radar with a frequency adjustable receiver. The radar pulse interrogates project aircraft equipped with transponders. The transponders reply with coded pulses at the radar receive frequency, which is slightly different from the transmit frequency. In this mode of operation, only aircraft equipped with transponders can be detected by the radar, and weather echoes are not observed.

The X-Band characteristics are as follows:

transmitted frequency	9.475	GigaHertz
receive frequency	9.410	GigaHertz
Pulse repetition frequency	478	Hertz
pulse duration	2	microsecond
typical peak power	100	kiloWatt
polarization	vertical	
beam width horizontal	1	degree
beam width vertical	16.5	degree
antenna rotation rate	14	rpm maximum
elevation program	none	

Because of the large vertical beam width, no elevation drive is required. This type of antenna is known as a pillbox antenna.

2.1.2 Radar receivers

2.1.2.1 Preamplifiers

The preamplifiers have a bandwidth of 1.6 MHz or 3 MHz (C-Band, S-Band respectively) and a power gain ratio of nominally 300 (25 dB). The preamplifiers amplify the 30 MHz IF signal from an RF/LO mixer stage. From this point on, all signals flow in coaxial cables.

2.1.2.2 Logarithmic amplifiers

The logarithmic amplifiers operate on the 30 MHz IF signals from the preamplifiers. Logarithmic amplifiers are devices which have logarithmic transfer functions. The logarithmic response is such that a plot of the input power in dB (see dB in appendix D), versus the logarithmic amplifier output in volts, produces a straight line. This allows the receiver to handle a large dynamic range of received power. A detector at the output of the logarithmic amplifiers filters out the 30 MHz IF signal leaving only a video signal for further processing.

2.1.2.3 Range integrators (C and S-Band radars only)

The range integrators average logarithmic video over 7 microsecond time intervals called "bins". A degree of noise reduction is afforded by range integration since range integration is performed on both noise and noisy targets. Range integration is implemented with two analog integrators and two sample-hold amplifiers for each video channel. One integrator is operating on the video signal while the others output is being displayed by its sample-hold amplifier. The integrators and sample-hold amplifiers interchange for alternate time periods. Range integration is performed in the C-Band and the C-Band/S-Band interfaces in a similar manner with the exception that each sample-hold outputs to an analog to digital converter.

2.1.2.4 Differential amplifier (S-Band radar only)

The differential amplifier produces the voltage difference between the range integrated port 1 and port 2 signals. Under normal operation, the antenna is set to transmit left hand circular polarization (see appendix B-I-ii). The port 2 signal is usually greater than port 1. A comparator ensures no output when there is only noise in port 1. The output signal of the differential amplifier is called the Circular Depolarization Ratio (CDR).

CDR = 10log10 (Power at Port 1/Power at Port 2).

2.1.2.5 Grey scale system (C and S-Band radars only)

The grey scale system produces output voltages corresponding to the values of the reflectivity or CDR as is indicated in Table 2.1. The higher the output voltage of the grey scale Generator, the brighter the PPI display will become. This arrangement produces an isocontoured PPI display in which the various levels are bounded by one another. Isocontouring aids a PPI operator in distinguishing various regions of a storm.

2.1.2.6 Phase discriminator (S-Band radar only)

The phase discriminator differentiates the phase between port 1 and port 2 IF signals.It utilizes two double balanced mixers, one fed by IF signals of ports 1 and 2 and the other fed by a 90 degree phase shifted port 1 IF signal and an unaltered port 2 IF signal. The respective outputs are the cosine and sine of the phase difference between port 1 and port 2 signals.

A coaxial switch on the input of this unit controls the flow of IF signals to either the precision test receiver for calibration purposes, or to the phase discriminator and logarithmic amplifier for normal operation.

Table 2.1 Grey scale thresholds and voltages

LEVEL	REFLECTIVITY PORT 2 (-dB)	S-Band VOLTAGE OUT	CDR (-dB)	VOLTAGE OUT
1	100 to 85	1.40V	25 and down	2.00
2	85 to 70	2.05V	20 to 25	1.50
3	70 to 60	0.50V	15 to 20	1.30
4	60 to 50	1.40V	10 to 20	1.10
5	50 and up	2.05V	5 to 10	1.00

LEVEL	C-Band REFLECTIVITY (-dB)	VOLTAGE OUT
1	95 to 82.5	1.40V
2	82.5 to 70	2.05V
3	70 to 60	0.50V
4	60 to 50	1.40V
5	50 and up	2.05V

2.1.2.7 Phase integrators (S-Band radar only)

The phase integrators average the phase discriminator output signals over 7 microsecond time intervals in the same manner as do the range integrators.

2.1.2.8 Analog to digital converters (S-Band and C-Band radars only)

Range integrated video signals (port 1 and port 2) and phase integrated phase signals (port 3 and port 4) are digitized into 8 bit binary words by analog to digital converters (ADC). The ADC input circuits are adjusted to accommodate input signals corresponding tc a return power dynamic range of -100 dBm to -30 dBm or a phase dynamic range of sine 0 to 1. Analog to digital conversion is performed in the C-Band and C-Band/S-Band interfaces in a similar manner with the exception that there are two analog to digital converters for each channel.

2.1.2.9 Azimuth integrators (S-Band and C-Band radars only)

The S-Band radar system has four azimuth integrators, one for each power and phase channel. Each azimuth integrator adds the binary data of the same range bin locations for a programmable number of consecutive radar pulse rays. The number of rays integrated is selected to provide averaging over one azimuth degree. Azimuth integration is performed in the C-Band and the C-Band/S-Band interfaces in a similar manner. Additional information may be obtained by referring to ASD Annual Report 1976, pages 46 to 49.

2.1.2.10 Memory buffers and multiplexer (S-Band and C-Band radars only)

The memory buffer and multiplexer manipulate data from the azimuth integrator into the format required by a computer direct memory access (DMA). The memory buffer provides temporary data storage to allow quasi asynchronous data transfer between the azimuth integrator and the DMA. The multiplexer sequences the data words such that the odd numbered words consist of the two power component channels data and the even numbered words consist of the two phase component channels data. The buffer memories in the C-Band and the C-Band/S-Band interfaces function in a similar manner.

2.1.2.11 Computer interface

There are four Radar/Computer interfaces in the radar trailer. One resides in the 11/44 computer cabinet. It interfaces either the C-Band video and antenna positions or the S-Band video (Port 2) and antenna positions to the 11/44. Three interfaces reside within the 11/34 cabinet. One interfaces the C-Band video and antenna positions to the 11/34. Another interfaces S-Band video Ports 1, 2, 3, and 4 only to the 11/34. The third resides within the 11/34 cabinet and interfaces aircraft positions, X-Band antenna positions, and either C-Band antenna positions or S-Band antenna positions to the 11/34.

2.1.2.12 Aircraft tracking unit (X-Band radar only)

Aircraft tracking is done using the X-Band radar. The airborne transponders transmit a coded signal when interrogated by X-Band transmitter pulses. The aircraft tracking unit decodes the transponder signals to identify the aircraft for synchronized display on a PPI and for computer logging. Aircraft appear as a series of dots and dashes on the PPIs and as a number on the computer generated real-time display.

The Aircraft Tracking Unit also digitizes the antenna positions of the X-Band, a Weather radar, and an Other radar. The Weather radar can be either S-Band or C-Band depending on the position of a Master Radar switch. Other radar is the unselected position of the Master Radar switch. Analog displayed aircraft are synchronized to the Weather radar azimuth positions.

2.1.3 Support systems

2.1.3.1 Computers

There are two main computers in the radar trailer. A PDP 11/34 is fitted with three Radar/Computer interfaces and various communication interfaces. Radar data acquired by the 11/34 are both logged onto magnetic tapes for archiving and processed for on-line real-time data display. A PDP 11/44 is fitted with one Radar/Computer interface and various communication interfaces. Radar data acquired by the 11/44 are processed for network acquisition by processor/displays.

2.1.3.2 Fiber optic transmission system (foundation)

A fiber optic link connects the radar site to building 38 via a 400 metre underground fiber optic cable. Fiber optic systems are a means of transmitting data via a light beam on a glass fiber. Optically transmitted signals are immune to radio frequency interference and electromagnetic interference. Fiber optic links provide low loss transmission over long distances comparing favorably with conductive cables in most respects and in this application are used to provide increased signal quality and reliability.

2.1.3.3 Plan position indicator

There are four PPIs in building 38, three are mounted in the control console, one is located in the Storm Chase Control room. There is one PPI mounted in the four-bay rack which is located in the radar trailer.

A PPI is basically a polar coordinate indicator producing a map-like display (see figure 1.6).

Range is marked-off as radial distance by range rings in 10 statute mile intervals, with every sixth ring accented. Azimuth is marked in degrees on a circular graticule around the circumference of the CRT. Elevation is displayed on a digital display built into the master console.

2.1.3.4 Range ring generator

The range ring generator's primary function is to generate a signal which creates concentric rings on a PPI display. The first ring occurs 10 statute miles from the origin with successive rings 10 statute miles farther away. Accented 60 and 120 mile rings are provided to ease range calculations by PPI display operators. The range ring generator uses the crystal timebase from the System Trigger Generator to generate range rings. The range ring generator also generates timing signals for the C-Band Range Integrator, the Phase Integrators, and the S-Band Range Integrators.

2.1.3.5 Remote data transmission system (EMSC)

The remote data transmission system transmit unit combines and formats radar data for transmission to a master control console in building 38 via a fiber optic link. Grey scaled video from a selected radar is combined with range rings, aircraft position markers, and trigger pulses into a single analog signal. Azimuth and elevation data from the selected radar are digitally combined with real time clock data, which is generated within the remote data transmission system transmit unit. A corresponding remote data transmission system receive unit in building 38 converts combined radar signals and data into composite video, trigger, and synchro signals for driving the PPI displays and data drivers to run the elevation and time displays in the master control console.

2.1.3.6 S-Band monitor

The S-Band Monitor is a (CW) signal source mounted on a 30 metre tower located 400 metres from the S-Band radar. It is able to transmit linear, left hand circular, or right hand circular polarization signals. Signals from the Monitor are used for calibration to ensure that the S-Band antenna is functioning correctly.

2.1.3.7 Standby power generator (Cummins)

The standby power generator is used to operate all electronic systems in case of a power failure or as the primary source of power during lightning storms over the radar antennas.

2.1.3.8 Statistical multiplexers

The statistical multiplexers (Gandalf) combine and format asynchronous serial computer communications ports (RS232C) into a high speed synchronous link for bidirectional communication between the radar site and building 38 via high speed modems and the fiber optics transmission system.

2.1.3.9 System trigger generator

The system trigger generator provides the radar systems and support equipment with a synchronizing signal called the System Trigger. It is used to initiate the pulsing of the radar transmitters and to initialize the action of signal processing equipment. System Trigger has a repetition frequency (PRF) of 478 Hertz and is either undelayed or delayed. Undelayed trigger preceeds the delayed trigger by 7 microseconds (one bin time interval). Undelayed System Trigger is used to control the C-Band transmitter, the S-Band transmitter, and various signal processing elements which must preceed integrated video. Delayed System Trigger is used to control the X-Band transmitter, radar displays, and various signal processing elements which must accompany integrated video. System Trigger outputs are distributed by video distribution amplifiers.

The system trigger generator derives the timing for System Trigger pulses from an internal crystal controlled timebase. The timebase oscillator signal is used by the range ring generator, the X-Band receiver, the aircraft tracking unit, and the S-Band Radar/Computer interface. The timebase outputs are driven by digital compatible buffers.

2.1.3.10 Test receiver (Ailtech)

The Precision Test Receiver is a tuned 30 MHz receiver designed for precise measurements of power level changes by means of the "direct IF attenuation substituation" method. It is used for the isolation checks of the S-Band antenna and the S-Band Phase Discriminator.

2.1.3.11 Video distribution amplifiers

These are video bandwidth amplifiers which directly drive coaxial cables. They serve to protect signal sources from loading and transmission line effects and preserve cable characteristic impedances.

2.2 Introduction to measurement and test equipment

Sophisticated equipment is required to test the performance of the radar systems. The aim of this section is to familiarize radar assistants with the equipment used on the radar site. For applications not covered in this section consult your supervisor or the appropriate technical manuals. Under no circumstances should you proceed without adequate prior knowledge. Personal safety is a prime concern of the radar staff. Dangerous high voltage and radiation are associated with some of the equipment, injury could occur! COMMON SENSE is very important here, USE IT!

The most commonly used equipment are listed in this section. The AR (Alberta Research Council) numbers referred to are manual numbers. Typically this list includes the following:
Multimeters
Power meters
Power supplies
Oscilloscopes
Waveform generators
Frequency counters
Synthesized signal generator
Spectrum analyzers
Wavemeters

2.2.1 Basic

2.2.1.1 Multimeters

Multimeters are important tools in an electronics lab. There are four digital multimeters in the radar trailer : Fluke Model 8000A (AR0095), Dana Model 3800A (AR0026), Data Precision Model 245 (AR004), Fluke Model 8050A, and one moving coil meter.

2.2.1.2 Power meters

There are two power meters on the radar site, a Hewlett Packard Model 435A (AR0099) and a Hewlett Packard Model 436A. The Hewlett Packard power meters are able to accept different models of power sensors. We have 2 Hewlett Packard power sensors in the lab. One model 8481A (AR0086) is a thermocouple detector and one model 8484A (AR0086) is a crystal diode detector.

2.2.1.3 Power supplies

There are three models of power supplies used in the radar lab for general purpose maintenance. Hewlett Packard Model 6205B (AR0012), Hewlett Packard Model 6285A (AR0011), and the Anatek Model 25-2.0D (AR0036).

2.2.2 Time domain

2.2.2.1 Oscilloscopes

2.2.2.1.1 Hewlett Packard 1703A (AR0013)

The model 1703A is a lightweight portable scope capable of measurements up to 35 MHz and with the additional capability of storing traces on the CRT.

2.2.2.1.2 Tektronix 475

The model 475 is a lightweight portable scope equipped with a detachable battery pack and is capable of measurements up to 200 MHz.

2.2.2.1.3 Tektronix 7403N (AR0017, AR0018 and AR0020)

Model 7403N is a portable oscilloscope that is used for general maintenance of equipment in the radar trailer. The 7403N includes two Dual Trace Amplifiers (7A18A) with a bandwidth from DC to 75 Mhz. It also includes a Dual Time Base (7B53A) that can be triggered up to 100 Mhz.

2.2.2.1.4 Tektronix R7603 (AR0127)

Model R7603 is a rack mounted oscilloscope that has 2 Dual Trace Amplifiers (7A26) with a bandwidth up to 200 MHz and a Dual Time Base (7B53A) with a triggering capability up to 100 MHz. It is used as our main calibration and general purpose scope.

2.2.2.2 Waveform generators

2.2.2.2.1 Dana Exact 516 (AR0114)

This is a versatile function generator for general use in the laboratory. It also provides backup pulse modulation for the radar calibrations.

2.2.2.2.2 Tektronix 2101 (AR0019)

The Tektronix 2101 is a general purpose pulse generator, capable of generating pulses as narrow as 20 ns. It can be used as a pulse modulation source for the Hewlett Packard 8673A signal generator or by itself for general purposes.

2.2.3 Frequency domain

2.2.3.1 Frequency counters

2.2.3.1.1 Hewlett Packard 5302A (AR0014)

Model 5302A is capable of counting signals up to 50 MHz.

2.2.3.1.2 Hewlett Packard 5345A (AR0001 and AR0080)

Model 5345A is capable of directly counting up to 500 MHz and with the use of the Frequency Converter Model 5255A, it is capable of counting from 2.6 GHz to 12.6 GHz.

2.2.3.2 Synthesized signal generator Hewlett Packard 8673A

The 8673A signal generator is used to calibrate the radar receiver systems. It is capable of generating Super High Frequency signals from 2.0 Ghz to 26 Ghz.

2.2.3.3 Spectrum analyzers

2.2.3.3.1 Hewlett Packard 141T (AR0076, AR0077 and AR0078)

The Hewlett Packard Spectrum Analyzer consists of a RF section model 8555A, IF section 8552B and Display Section Model 141T. It has a frequency range of 10.0 Mhz to 18.0 Ghz.

2.2.3.3.2 Tektronix 492P

The 492P Spectrum Analyzer is a high performance spectrum analyzer which is equipped with a General Purpose Interface Bus for remote control. The 492P can alphanumerically display setup parameters and signal parameters. The 492P has a frequency range of 50 kHz to 21 GHz with an internal coaxial mixer, and up to 140 GHz with optional external waveguide mixers.

2.2.3.4 Wavemeters (AR0102)

There are three wavemeters in the laboratory: FXR model N410A used for S-Band measurements, Hewlett Packard Model 537A used for C-Band and X-Band measurements, and Atelco model DBG710-2 which is mounted on the transponder test set.

Chapter three: Operation

3.1 Electronic systems

In this section instructions for the operation of the radar systems and subsystems are given. Essentially, these illustrate procedures to turn on the following systems:
C-Band antenna and transceiver
S-Band antenna, transmitter, and receiver
X-Band antenna, transceiver, and ATU
Computers
Fibre optic transmission system
S-Band monitor
Standby generator
Statistical multiplexers
Real time clock system
Remote data transmission system
Test receiver

3.1.1 C-Band

3.1.1.1 Antenna

The C-Band antenna has two independent drive systems, one for azimuth and one for elevation. The azimuth drive can be operated in on one of two modes: manual or automatic. In the manual mode, the antenna position is controlled by a handwheel. In the automatic mode, the antenna rotation speed is controlled from 0 to 8 rpm. The elevation drive can be operated in one of two modes: manual or automatic. In the manual mode, the antenna position is controlled by a handwheel. In the automatic mode it elevates in 1.5 degree steps to a selectable end position.

High power microwave radiation is extremely hazardous. It is known that the hangar roof is radiated by the C-Band radar when the antenna elevation is less than 2 degrees. Antennas should therefore be rotating before the transmitters are turned on.

Ensure that no work is in progress and that no personnel are on the towers or are inside the radome.

To operate the antenna follow these procedures. Refer to figure 3.1.

1. Check that it is safe to rotate the antenna.
2. Turn the POWER on.
3. Turn the DRIVE POWER on.
4. Set the Azimuth MODE to AUTOMATIC.
5. Set the ELEVATION MODE to MANUAL or AUTOMATIC. In the manual mode, the elevation is controlled by the hand wheel on the front panel. To operate in the automatic elevation mode, first manually adjust elevation to 0 degrees. Switch to automatic mode. Antenna will now scan in 1 1/2 degree steps to 9 or 21 degrees as selected by the 9/21 degree switch.
6. To stop the antenna, turn the DRIVE POWER to off.
7. Switch off PPI displays when antenna is not rotating to prevent the trace from burning the phosphor of the CRT; or select another rotating antenna.

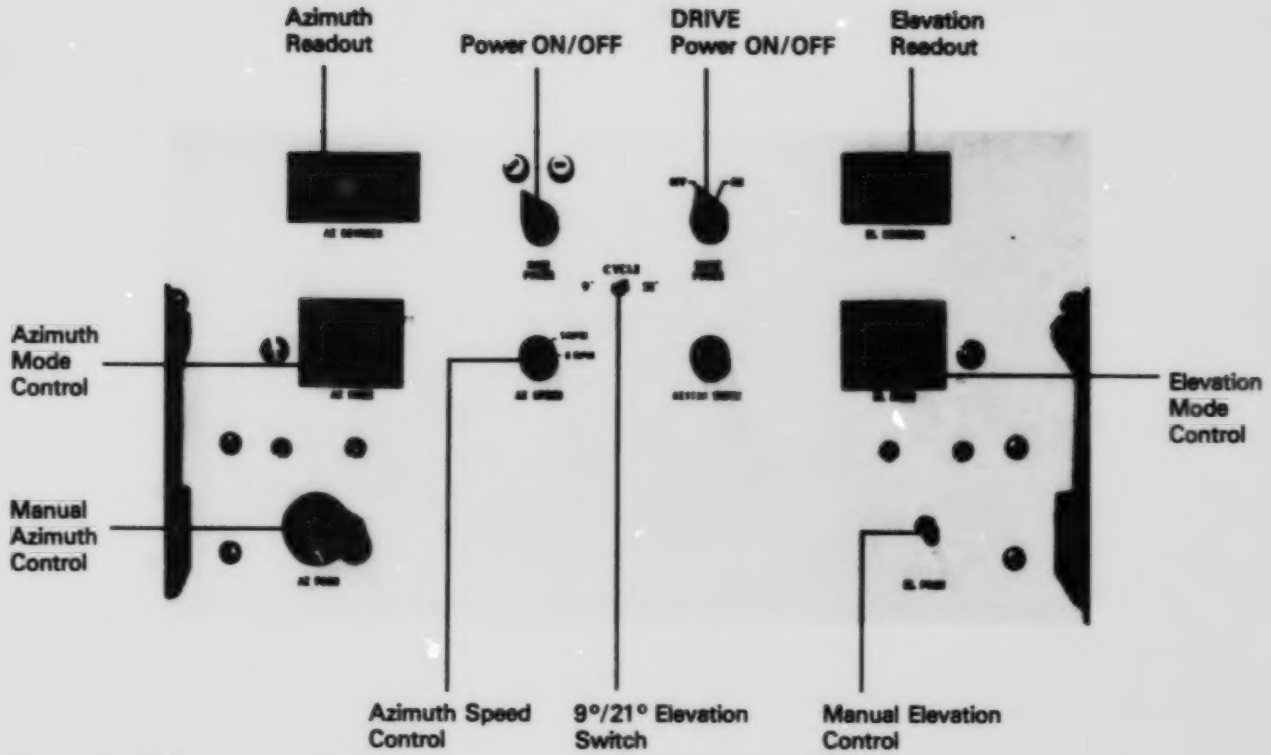


Figure 3.1 C-Band antenna controller

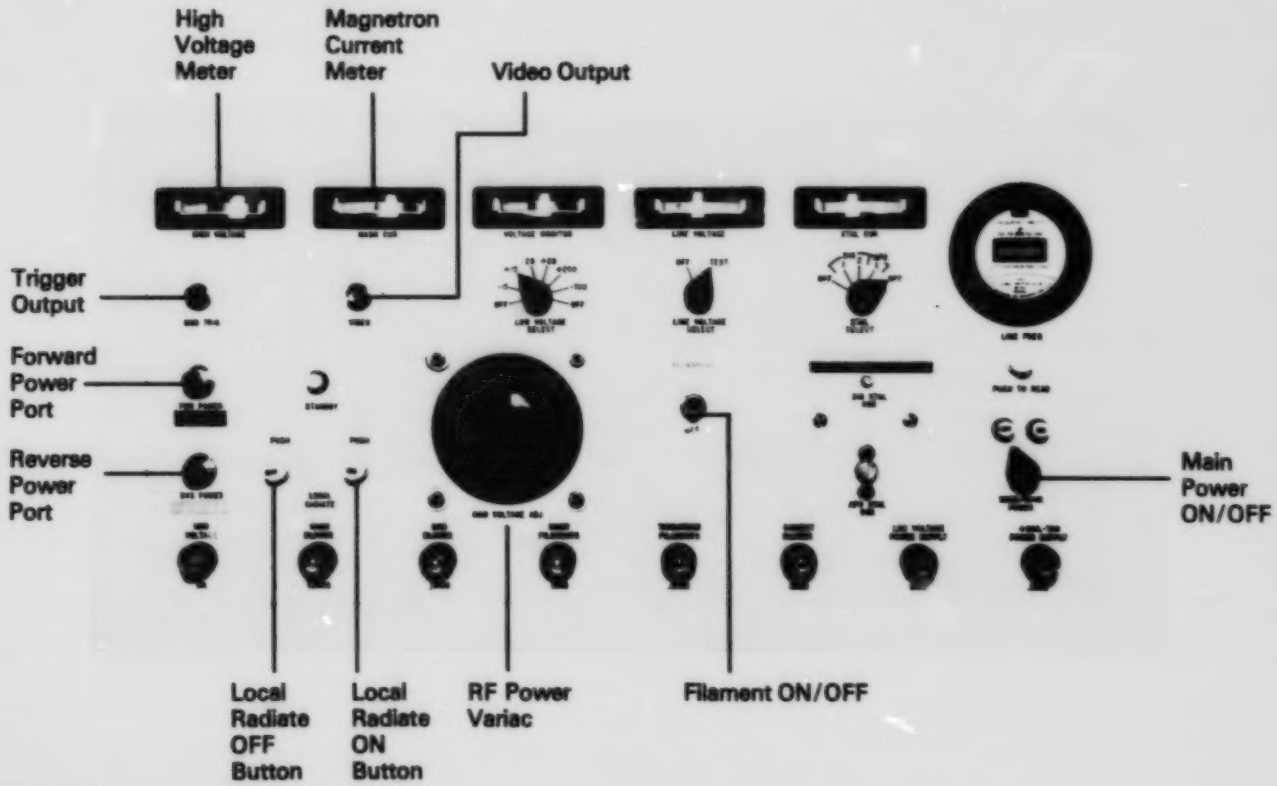


Figure 3.2. C-Band transceiver

Figure 3.3. Inside the C-Band transceiver

Figure 3.4 S-Band antenna controller

3.1.1.2 Transceiver

1. Check that the antenna is rotating and the elevation is set to the automatic mode.
2. The C-Band is equipped with a coaxial magnetron. Upon starting a slow run up to maximum power using the Variac is not required, the Variac is preset and not touched. To apply 120 vac power to the transmitter cabinet, position the XMITR/RCVR switch to ON.
3. The front panel of the transmitter has eight fuses mounted on it. These fuses are equipped with neon lights which will come on if a fuse should burn out. If any of these lights are on DO NOT ATTEMPT TO ACTIVATE THE RADIATE BUTTON.
4. Open the transmitter cabinet and confirm that the frequency control switch is set to automatic.
5. Set the filament switch to the ON position.
6. After a 5 minute delay the orange STANDBY light will illuminate. Push the LOCAL RADIATE ON button, it will light up and the LOCAL RADIATE OFF button will be extinguished. The transmitter is now radiating.
7. After C-Band operations have been completed, push the LOCAL RADIATE OFF button. The orange STANDBY light will illuminate and the LOCAL RADIATE ON button will be extinguished. The transmitter will now cease to radiate.
8. Turn the FILAMENT CONTROL switch to OFF for complete shut down. Main power switch is normally left on.

3.1.2 S-Band

3.1.2.1 Antenna

The S-Band antenna has two independent drive systems, one for azimuth and one for elevation. The azimuth drive can be operated in a high speed (labeled NORMAL) or a variable speed (labelled SLOW) mode. The elevation drive has three modes: automatic, standby, and manual. Refer to figures 3.4 and 3.5 .

The antenna azimuth hatch is equipped with a safety interlock. If this door is open, or not tightly shut, the pedestal drives will be disabled. Ensure that no calibration cables are connected to the antenna before beginning antenna motion.

High power microwave radiation is extremely hazardous. It is known that the hangar roof is radiated by the C-Band radar when the antenna elevation is less than 2 degrees. Antennas should therefore be rotating before the transmitters are turned on.

Ensure that no work is in progress and that no personnel are on the towers or are inside the radome.

3.1.2.1.1 Azimuth

Slow speed azimuth drive

1. Check that it is safe to rotate the antenna.
2. Set AZIMUTH DRIVE CONTROL to SLOW.
3. Engage slow speed DRIVE and CLUTCH switches; the two red indicator lights should come on.
4. Turn SPEED CONTROL clockwise for clockwise rotation and counter-clockwise for counter-clockwise rotation.
5. To stop the antenna, set SPEED CONTROL at center position; disengage CLUTCH and DRIVE when not using the antenna.
6 The slow speed drive is used to position the antenna at the appropriate azimuths for the applications listed below:
   a) Antenna calibration: 53.2 degrees azimuth, 2.19 degrees elevation,;
   b) Service in upper housing: 45 degrees azimuth,
   c) Major calibration: 210 degrees azimuth.

A warning sign must be posted on the antenna controller when personnel are required to ascend the S-Band tower and when the calibration cable is connected to the lower waveguide for major calibration. The clutch and drive should be engaged to prevent the antenna from being moved by the wind. If the wind speed is high (greater than 30 mph or 50 km/hr) the clutch and drive should be turned off to allow the antenna to move freely. Do not connect the calibration cable under these conditions.

Normal speed azimuth drive

1. Check that it is safe to rotate the antenna.
2. Set AZIMUTH DRIVE CONTROL to NORMAL. Switch slow speed DRIVE and CLUTCH to OFF.
3. Press AZIMUTH START button. Antenna will rotate at 8 rpm.
4. Press AZIMUTH STOP button to stop antenna.
5. To stop the antenna in automatic elevation mode, press CYCLE STOP button. Antenna will stop after elevation cycle is completed.
6. When the antennas are not rotating any plan position indicator displays must be switched off or their video intensities turned down. High intensity, stationary traces can severely burn the phosphor of PPI CRT's in a very short period of time.

3.1.2.1.2 Elevation

Standby elevation mode

1. The antenna will not elevate in this mode.

Manual elevation mode

1. In this mode, the antenna elevation is controlled by the UP-DOWN switch or the ELEVATION POSITION SYNCHRO.
2. The elevation limits (approximately -1 to 22 degrees) are set by elevation limit switches in the upper housing of the antenna pedestal.

Automatic elevation mode

1. In this mode, the antenna will execute a spiral scan to 8 or 20 degrees as selected by the 8/20 switch. The spiral scan rate is one degree of elevation per azimuth revolution. Twelve revolutions are required to complete an 8 degree scan and 24 revolutions for a 20 degree scan.
2. The settling position of the antenna on completion of a cycle can be adjusted by the ELEVATION POSITION SYNCHRO. This should be set to 0 degrees.
3. When in the automatic elevation mode, the antenna is usually set to rotate at normal speed.

3.1.2.1.3 Polarization and phase

The polarization and phase controller allow an operator to change the polarization of the transmitted signal and the axis of orientation of a linearly polarized transmitted signal.

The polarization is changed with the Polarization Motor Switch. The switch has three positions: up, center, and down. A spring returns the switch to its center position. The up position will change the polarization to a higher indicator reading. The center position is the off position. The down position will change the polarization to a lower indicator reading.

The polarization is usually set to one of three settings. These settings are:

58525 LINEAR
59403 LEFT HAND CIRCULAR
63000 RIGHT HAND CIRCULAR

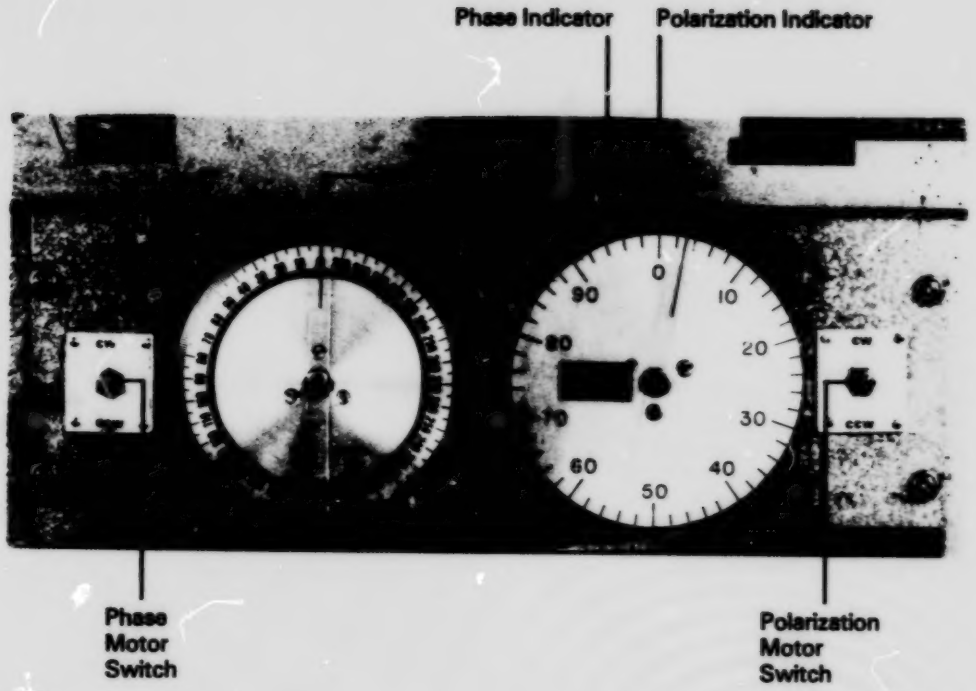


Figure 3.5. S-Band polarization and phase controller

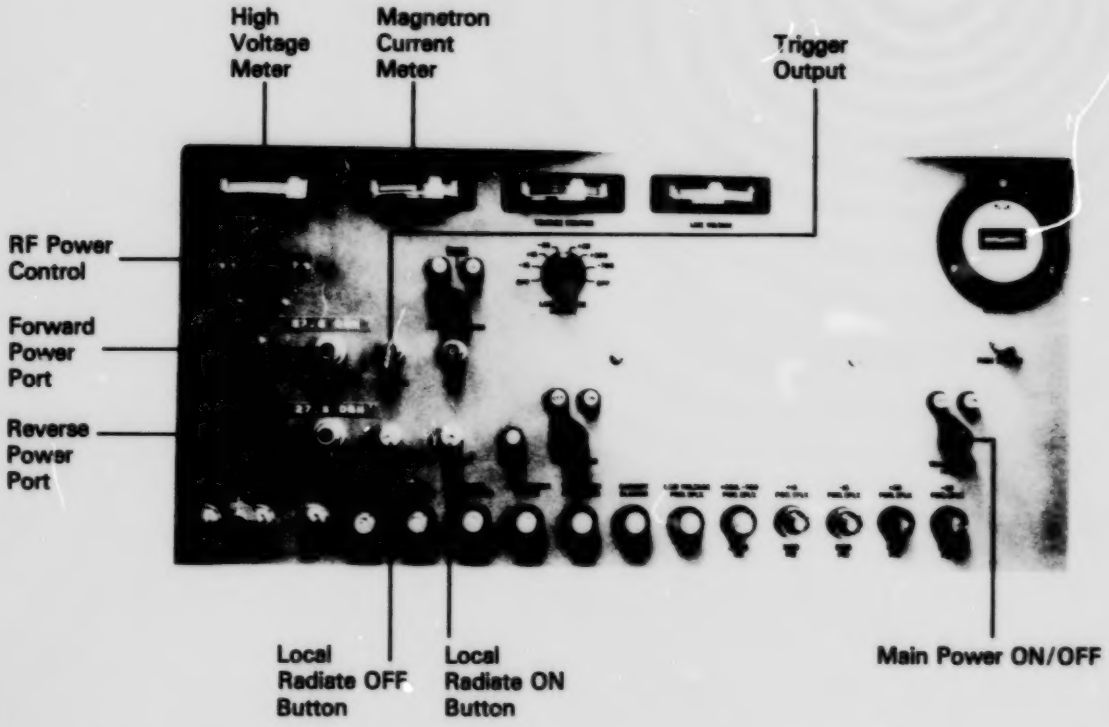


Figure 3.6. S-Band transmitter

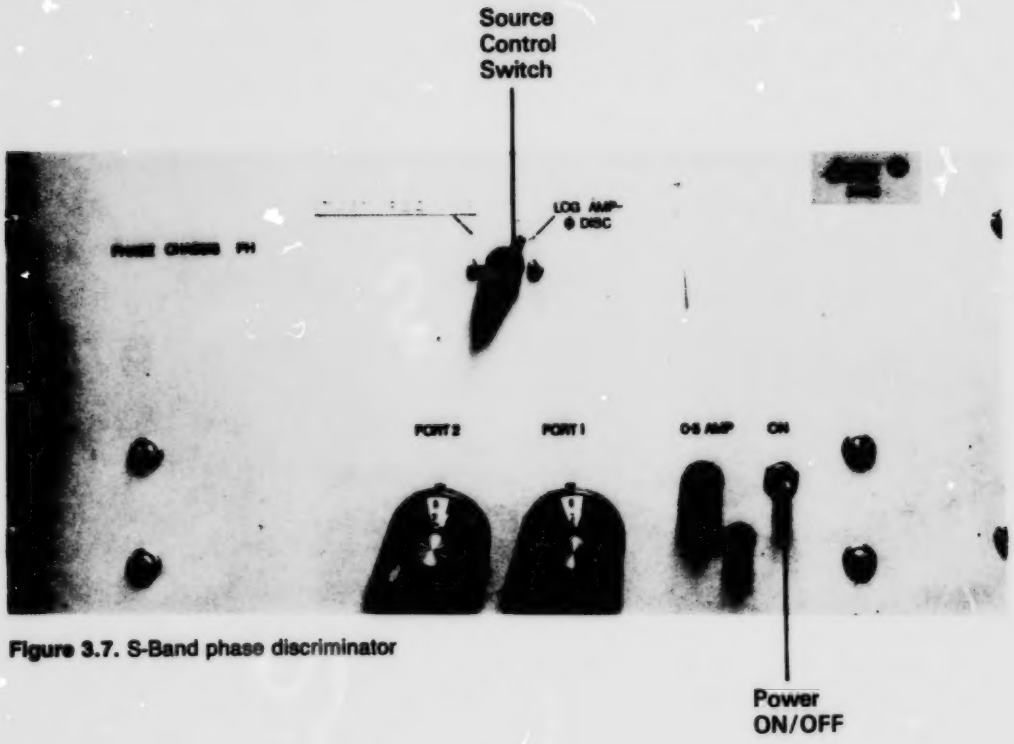


Figure 3.7. S-Band phase discriminator

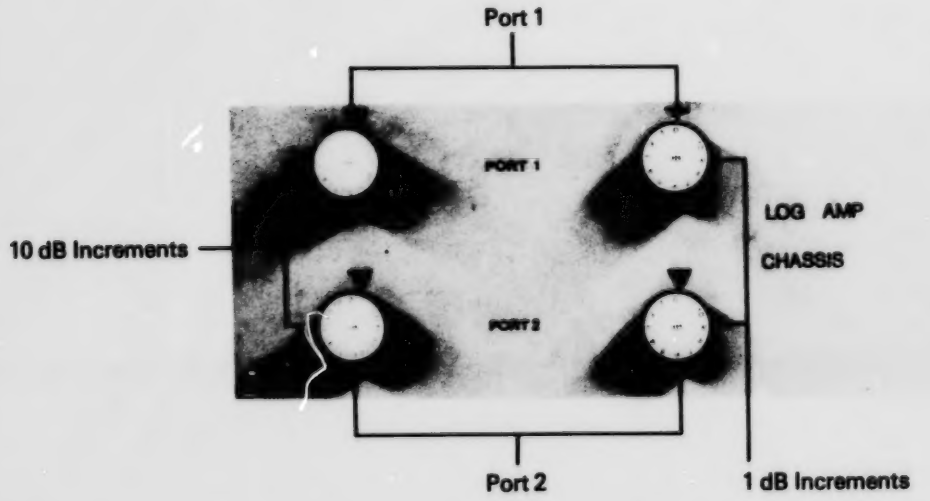


Figure 3.8. S-Band logarithmic amplifier attenuators

For normal operation the antenna is set to transmit LEFT HAND CIRCULAR.

The POLARIZATION CONTROL DIAL READING MUST NOT EXCEED 68850 OR GO BELOW 57810.

The phase is changed with the Phase Motor Switch. The switch operates similarly to the Polarization Motor Switch. For normal operation, the phase setting is 0 degrees.

Note: When setting the polarization or phase controls, always approach the desired readings from the clockwise direction to eliminate backlash error.

3.1.2.2 Transmitter

1. Check that the antenna is rotating at normal speed and the elevation control is set to the automatic mode.
2. The S-Band is equipped with a coaxial magnetron. Upon starting, a slow run up to maximum power using the Variac is not required, the Variac is preset and not touched. To apply 120 vac power to the transmitter cabinet, position the XMITR/RCVR switch to ON.
3. The front panel of the transmitter has eight fuses mounted on These fuses are equipped with neon lights which will come on if a fuse should burn out. If any of these light are on DO NOT ATTEMPT TO ACTIVATE THE RADIATE ON BUTTON. Inform your supervisor.
4. After an 8 minute delay the orange STANDBY light will come on. Push the LOCAL RADIATE ON button, it will light up and the LOCAL RADIATE OFF button will be extinguished. The transmitter is now radiating.
5. During transmitter operation the oil level should rise 2.5 centimetres. After S-Band operations are completed push the LOCAL RADIATE OFF button, the orange STANDBY light will come on and the LOCAL RADIATE ON button will be extinguished, the transmitter will cease to radiate.
6. Leave the XMITR/RCVR switch in the ON position. This will keep the cooling fans in operation to cool the pulse transformer. Cool air is drawn in through the vents on the front bottom of the transmitter. Do not switch off the fans until cool air is exhausted from the top vent, this should take about half a hour.

3.1.2.3 S-Band receiver

For normal operation the Phase Discriminator SOURCE CONTROL switch is set to the LOG-AMP position.

For normal operation the IF attenuators in the Logarithmic Amplifier Chassis are set to 0 dB attenuation.

3.1.3 X-Band

3.1.3.1 Antenna

The X-Band antenna controller is located on the same rack as the S-Band antenna controls. The X-Band antenna is a variable D.C. drive and can be set to any rate from 0 to a maximum of 14 rpm.

High power microwave radiation is extremely hazardous. It is known that the hangar roof is radiated by the C-Band radar when the antenna elevation is less than 2 degrees. Antennas should therefore be rotating before the transmitters are turned on.

Ensure that no work is in progress and that no personnel are on the towers or are inside the radome.

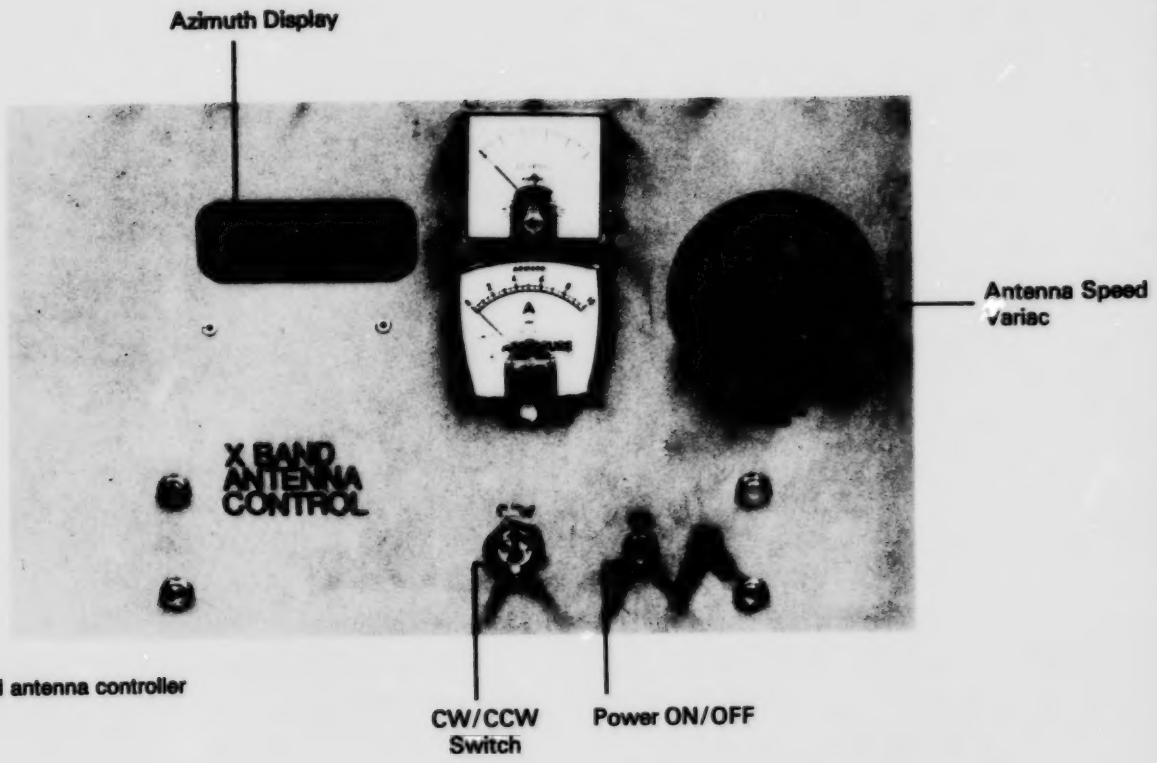


Figure 3.9. X-Band antenna controller

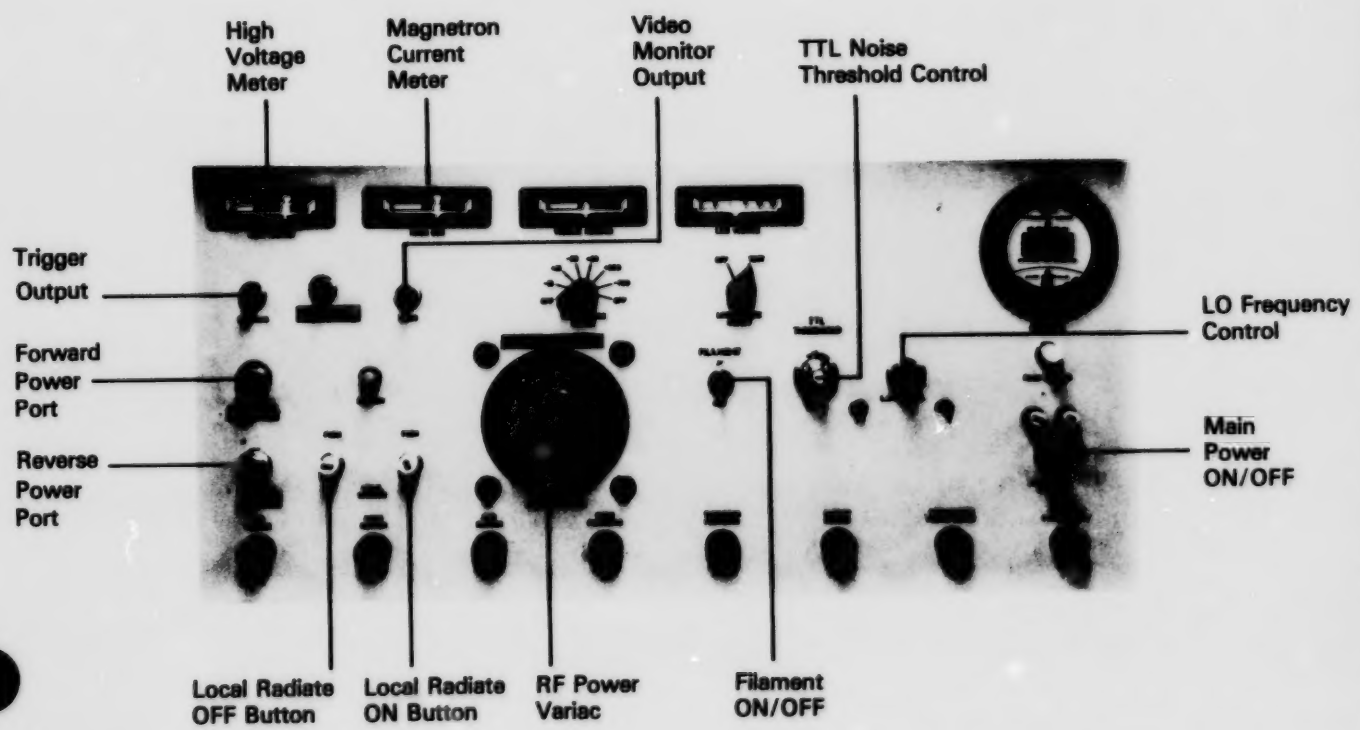


Figure 3.10. X-Band transceiver

To operate the antenna follow these procedures. Refer to figure 3.9.

1. Check that it is safe to rotate the antenna.
2. Rotate the Variac dial fully ccw, place the CW/CCW switch in the CW position.
3. Turn the power switch on. A red indicator light will come on.
4. Rotate the Variac dial cw slowly until the dial pointer is aligned with the marker dot corresponding to the number 85. This setting corresponds to an X-Band antenna rotation rate of approximately 10 rpm.

3.1.3.2 Transceiver

1. Open Transmitter cabinet and set the STC switch to the ON position.
2. Turn on MAIN POWER and FILAMENT CONTROL. Turn output RF POWER CONTROL VARIAC fully counter-clockwise.
3. After the time delay has expired, press the RADIATE ON button and turn the POWER VARIAC clockwise to obtain the rated output power level.
4. To turn the transmitter off, turn the variac fully ccw then press the RADIATE OFF button. Transmitter is usually left with the FILAMENT CONTROL switch OFF and the MAIN POWER switch ON.

The X-Band radar works in conjunction with the aircraft tracking unit (ATU) to detect aircraft. The ATU simulator master control switch must be in the X-Band position. Select reference radar according to Section 3.1.3.3.

3.1.3.3 Aircraft tracking unit

The aircraft tracking unit is an automatic digital system that requires no operations procedure. There are, however, three switches which must be set to certain positions for proper operation of the ATU. These are: Power On/Off, which is located on the back of the chassis, Reference Radar, which selects either the S-Band or C-Band radar as reference for aircraft position synchronization, and Simulator Master Control, which selects either X-Band video or the aircraft simulator to be the ATU input.

It is possible to simulate up to 4 similtaneous aircraft with the aircraft simulator. The front panel of the aircraft simulator is shown in figure 3.11. Refer to Section 4.1.3.4 on using the simulator to check the operation of the aircraft tracking unit.

A row of LEDs allows monitoring of the binary azimuth reading of weather radar azimuth (WAZ), other radar azimuth (OR), aircraft radar azimuth (AC), or weather radar elevation (WEL) as controlled by a MONITOR SELECT switch on the top left corner.

Four BNC outputs are monitor ports and are used for maintenance only.

For operation with C-Band video remoted to building 38 the ATU switches should be set to:

POWER	ON
REFERENCE RADAR	C-BAND
ATU MASTER CONTROL	X-BAND

For operation with S-Band logging by the 11/34 computer regardless of which video signal is remoted to building 38 the ATU switches should be set to:

POWER	ON
REFERENCE RADAR	S-BAND
ATU MASTER CONTROL	X-BAND

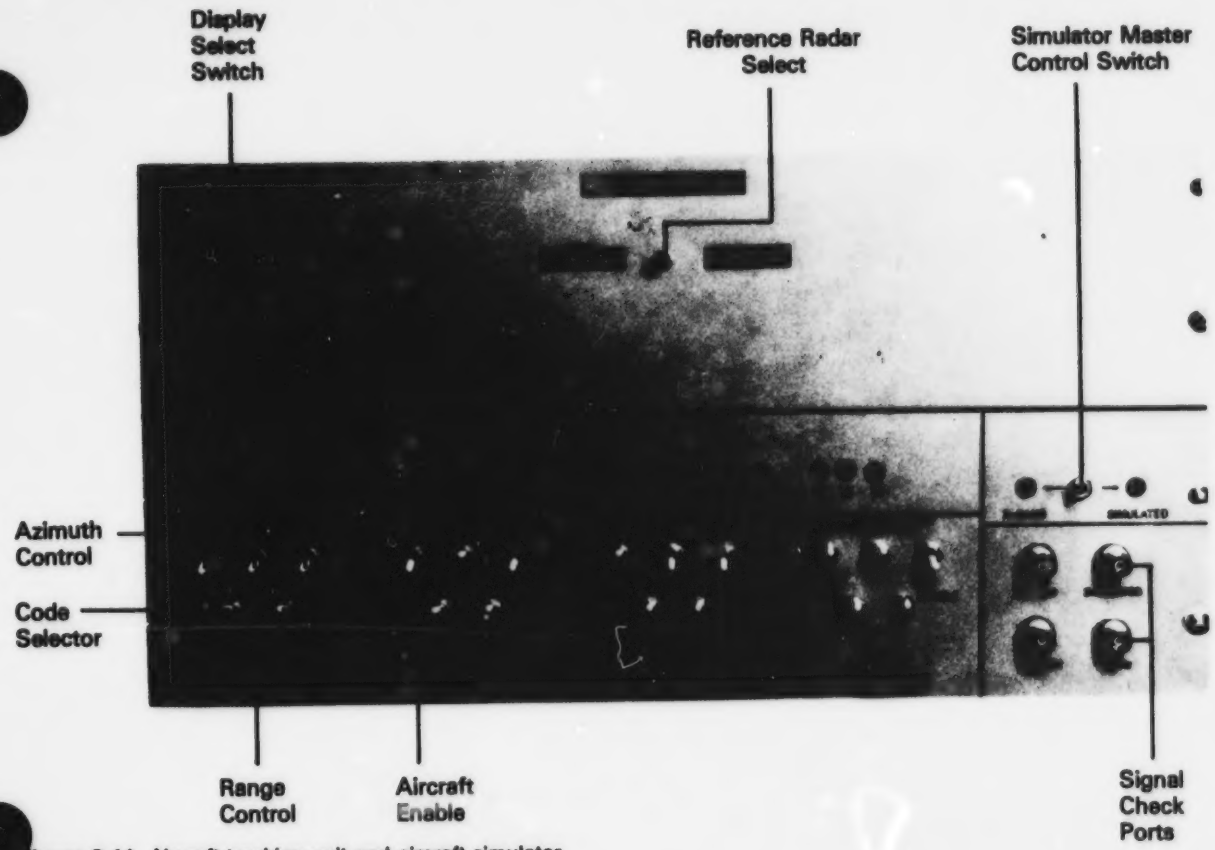


Figure 3.11. Aircraft tracking unit and aircraft simulator

3.1.4 Support

3.1.4.1 Computers

The 11/34 and 11/44 may fail on occasion due to power line fluctuations. In such cases the computers have to be restarted. The procedure is slightly different for each machine.

PDP 11/34

This machine has a numeric display, a keypad, and a key on the front of the computer cabinet. The keypad contains the usual numeric keys as well as a number of keys marked HALT, BOOT, CTRL, LADR, and so on. If a power failure has occurred the following steps must be followed:

1. Turn the key on the front panel to the DC OFF position. This turns off all power to the computer and the radar interfaces but not to the tape drives.
2. Turn the key on the front panel to the DC ON position. This action resets all circuits inside the computer and the radar interface to a known correct state. The computer is now ready to respond to commands from the keypad.
3. Insure that the two tape drives are powered up.
4. Press the key marked CTRL and the key marked BOOT on the keypad simultaneously. The run light should illuminate and the computer will print out a series of digits on the console followed by a "$" on a new line.
5. Respond to this prompt by typing "DL:" on the console. The two characters must be in upper case.

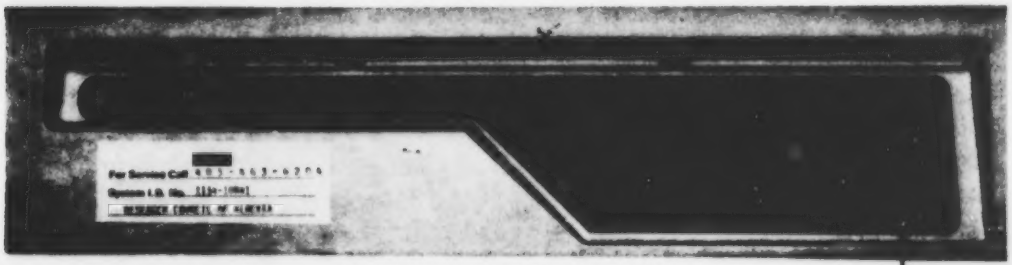


Figure 3.12 DEC PDP 11/34 Computer

Power ON/OFF Switch

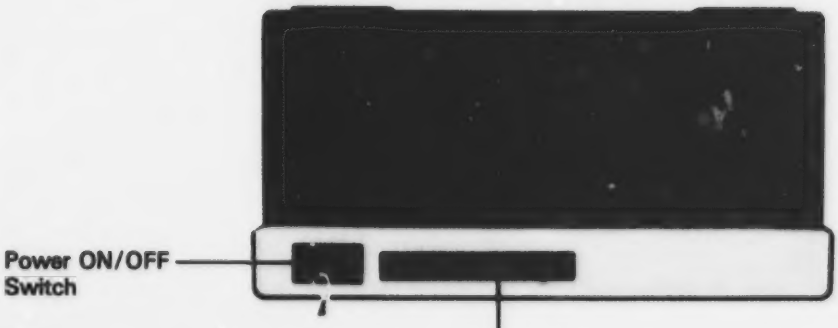


Figure 3.13 DEC PDP 11/44 Computer

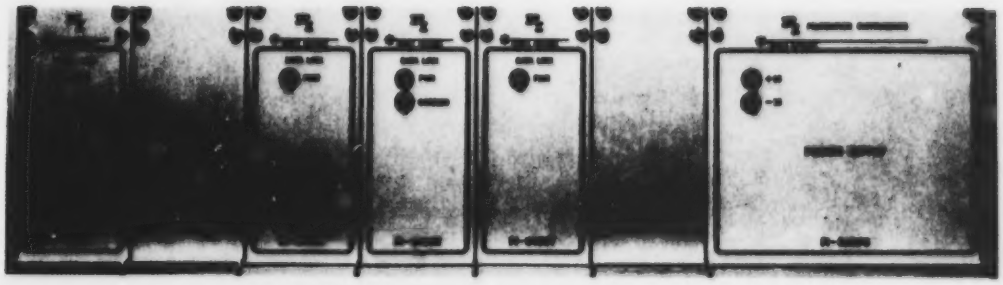


Figure 3.14 Foundation Instruments F1-6000 MF Mainframe

6. The computer will now go through a restart sequence. This initializes the many programs which allow the computer to respond to your commands. To complete this process a number of answers may be required from you. A print out from a previous computer start up has been posted on the bulletin board. Please answer the questions in the same way.
7. If the above procedure fails start over again with step one. Should the procedure fail again notify your supervisor since this usually indicates a failure requiring service from qualified personnel.
8. Now that the computer is running, turn the key on the front panel to the lock position. This prevents accidental activation of the keypad.

PDP 11/44

This machine is of a more recent vintage than the 11/34. Aside from the main processor that does all the work, it also includes a microprocessor which monitors the functions of the main processor. The console is connected to this microprocessor whenever the computer has had a power failure. This simplifies the start-up procedure somewhat.

1. Turn the key on the cabinet to the power off position
2. Turn the key to the LCL ENBL position. The microprocessor can now accept commands from the system console.
3. To get things going press the RUN/BOOT switch located under the key. The computer will respond with a string of numbers on the console.
4. Following the prompt ">>>" type "B DL:" to activate the restart procedure. As on the 11/34, a series of commands will be executed to bring the computer back to the normal running state. A sample print out of a restart has been posted on the bulletin board and you are expected to answer the questions in the same way.
5. Turn the key on the cabinet to the LCL DSBL position to prevent accidental activation of the microprocessor from the console. In the event that this procedure fails, return to step one. If the procedure fails a second time contact your supervisor to have the problem investigated.

3.1.4.2 Fibre optic transmission system (Foundation)

The multi channel fiber optic system is configured around a FI-6000MF mainframe. A plug-in power supply and an internal distribution bus provides all necessary power for any combination of up to six fiber optic modules.

Operation

There are no operator controls. All other adjustments and test points should be left alone.

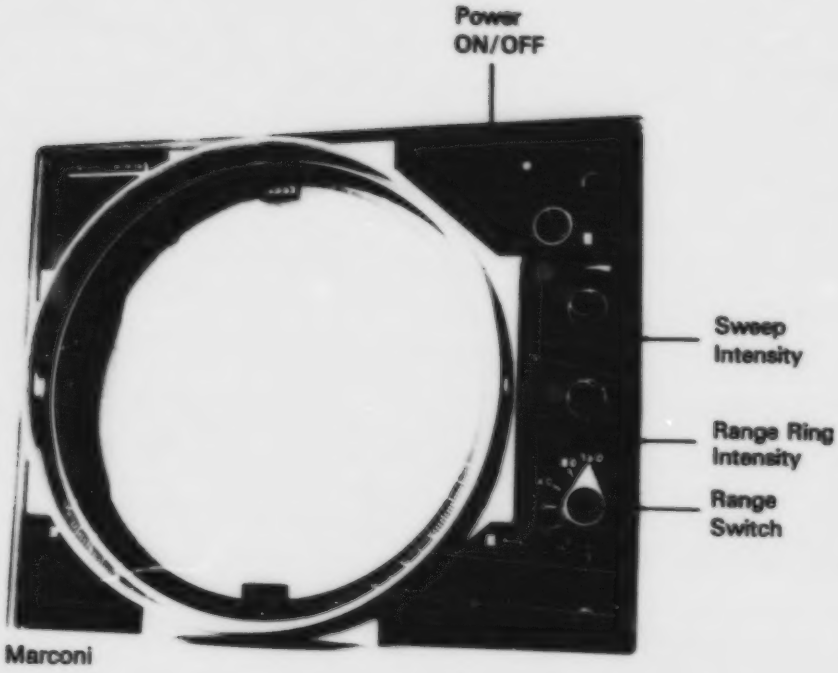
3.1.4.3 Plan position indicators

The PPIs provide radar displays in the control console, in the storm chase control room and in the four-bay rack. The PPI displays should be turned on only when they are viewing a radar with a rotating antenna, otherwise a stationary electron beam will burn the phosphor coating on the PPI tube face.

WHENEVER THE RADAR ANTENNAS ARE STOPPED THE PPIs MUST BE CHECKED TO ENSURE THEY ARE TURNED OFF.

To operate the PPIs follow these steps:

1. Turn the PPI main POWER ON.
2. Adjust the VIDEO INTENSITY and SWEEP INTENSITY for comfortable viewing.
3. Adjust the RANGE select switch for target area of interest.
4. Adjust the FOCUS, PANEL DIMMER, and AZIMUTH RING INTENSITY as necessary.
5. Adjust the PLOTTER INTENSITY as necessary when plotting on the screen.



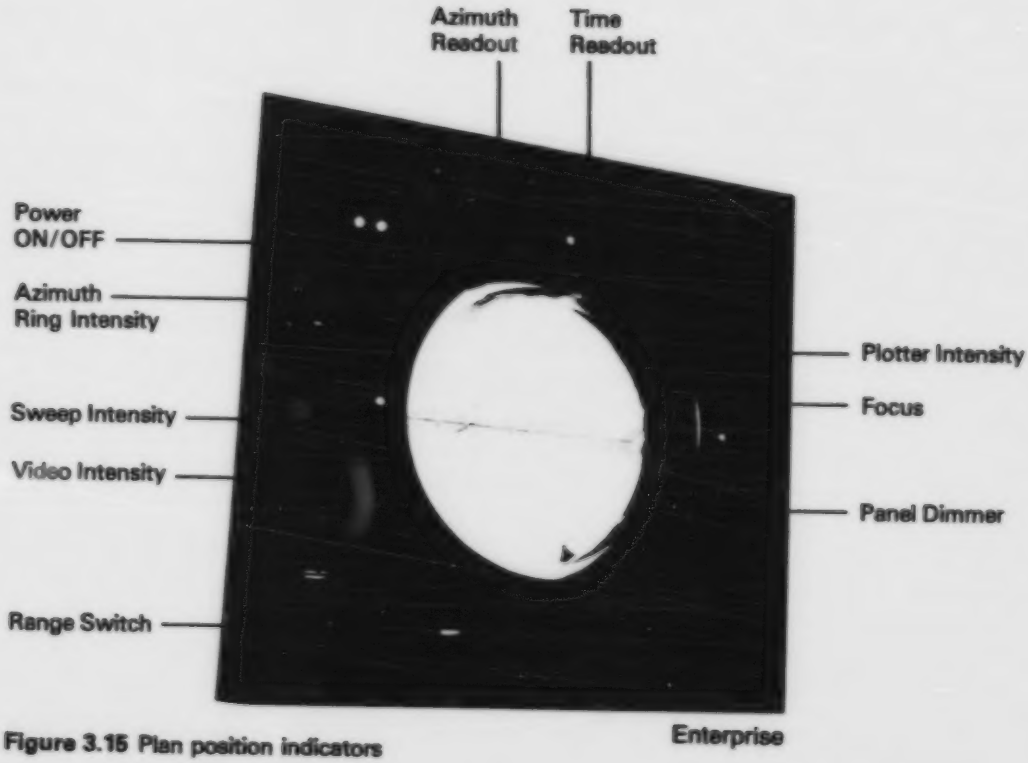


Figure 3.15 Plan position indicators

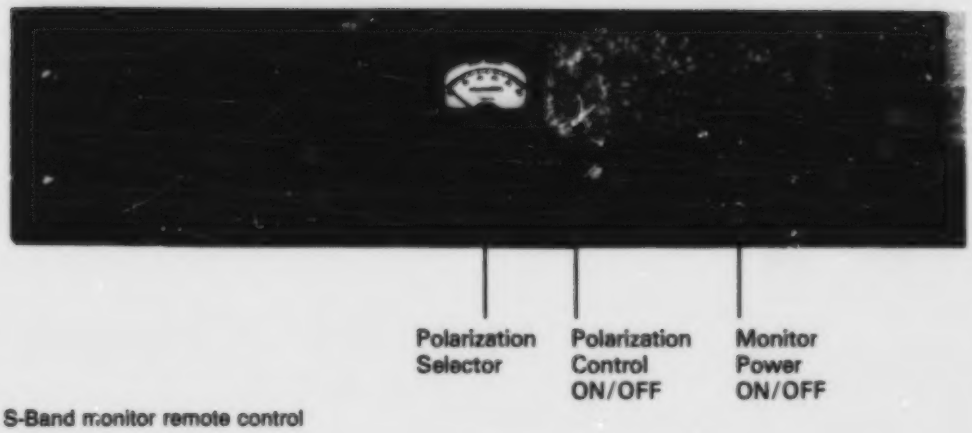


Figure 3.16. S-Band monitor remote control

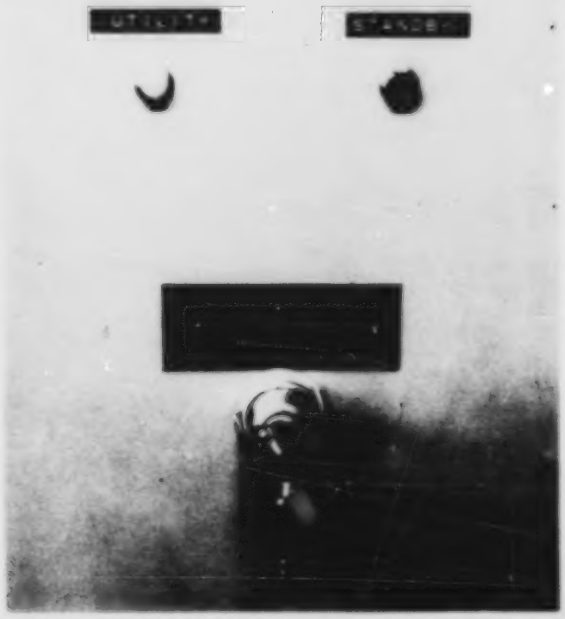


Figure 3.17. Emergency power transfer remote control switch

3.1.4.4 S-Band monitor

The S-Band Monitor is a (CW) signal source mounted on a 30 metre tower located 400 metres from the S-Band radar. It is able to transmit linear, left hand circular, or right hand circular polarization signals. Signals from the Monitor are used for calibration to ensure that the S-Band antenna is functioning correctly.

Remote control operation

Power to the Monitor circuits is enabled with the MONITOR POWER switch. When Monitor power is on, a crystal controlled frequency source within the Monitor oscillates and the Monitor remote control is enabled. Monitor power is off when not calibrating the S-Band Antenna or Phase discriminator.

The signal polarization that the Monitor transmits is changed with the POLARIZATION ON and RHC/LIN/LHC switches. The polarization circuits are enabled by turning the POLARIZATION ON switch to the ON position. The POLARIZATION RHC/LIN/LHC switch selects the polarization at which the Monitor polarization circuits will automatically stop.

The Monitor antenna rotation is changed with the ANTENNA CW ON and CCW ON switches. These switches are not changed during the course of normal operation or calibration procedures. Turning one of the switches on will cause the Monitor antenna to rotate in the direction selected and automatically stop at preset limits. The Monitor is normally set with the CW switch down and the CCW switch up to ensure that the Monitor antenna will transmit a linear polarized signal with a vertical axis.

A current meter on the Monitor unit controller is used to check the operation of the Monitor remote control circuits. The selection of a new polarization or antenna rotation will cause the current meter indication to increase until the selected circuits automatically stop.

Two colored incandescent lights indicate the status of Monitor control unit power and Monitor power. A blue light indicates that the power supply within the Monitor control unit is working. The blue light should be on at all times with the exception of a power failure or an S-Band system shutdown. A red light indicates that the Monitor itself is operating. The red light should be off during normal radar operation because the Monitor frequency source will interfere with S-Band reception.

3.1.4.5 Standby power generator (Cummins)

Procedure to transfer to generator power:

1. Check that there is sufficient fuel. The diesel engine uses 44 litres/hour and the present tank capacity is 1000 litres.
2. Turn the remote control switch from AUTO STANDBY to DIESEL RUN position. The diesel engine should start and keep running.
3. Turn the remote control switch from DIESEL RUN to SYCHRO TRANSFER and maintain until STANDBY light begins flashing then return the remote control switch to the DIESEL RUN position.

Procedure to transfer to utility power:

1. Turn the remote control switch from DIESEL RUN to AUTO STANDBY. When the generator system sychronizes and switches back to utility power, the UTILITY light will illuminate. The engine will automatically shutdown after a cool-down cycle.

3.1.4.6 Statistical multiplexer (Gandalf)

The Gandalf model PIN9103 is a Statistical Multiplexer which permits up to 32 asynchronous data links to be economically replaced by eliminating the multiple links and modems and concentrating the data onto a single high speed synchronous link.

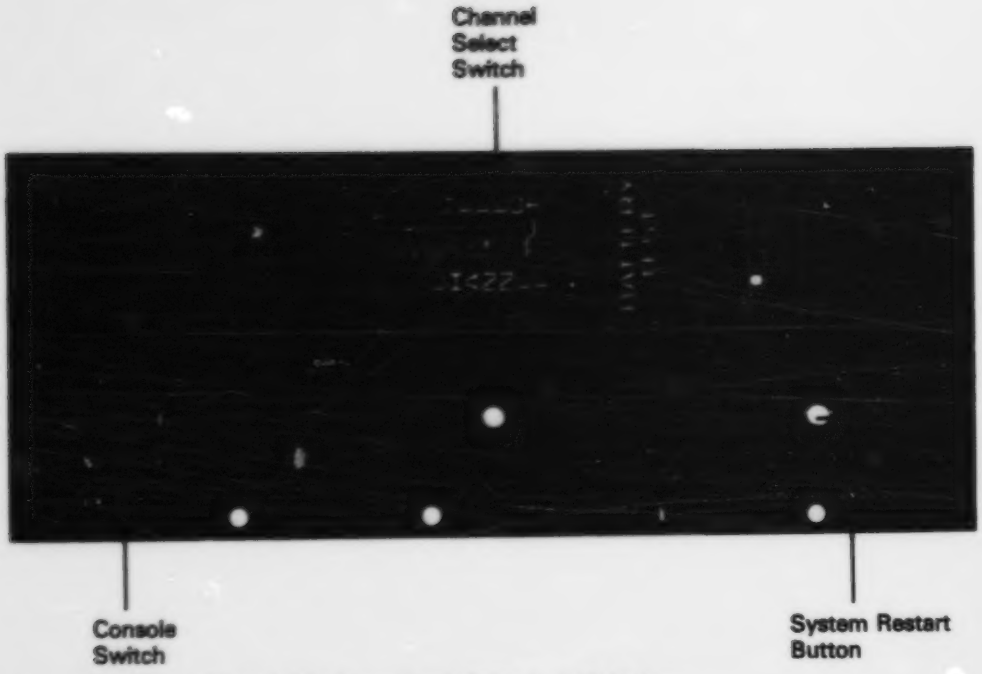


Figure 3.18 Gandalf PIN 9103 Front Panel Statistical Multiplexer

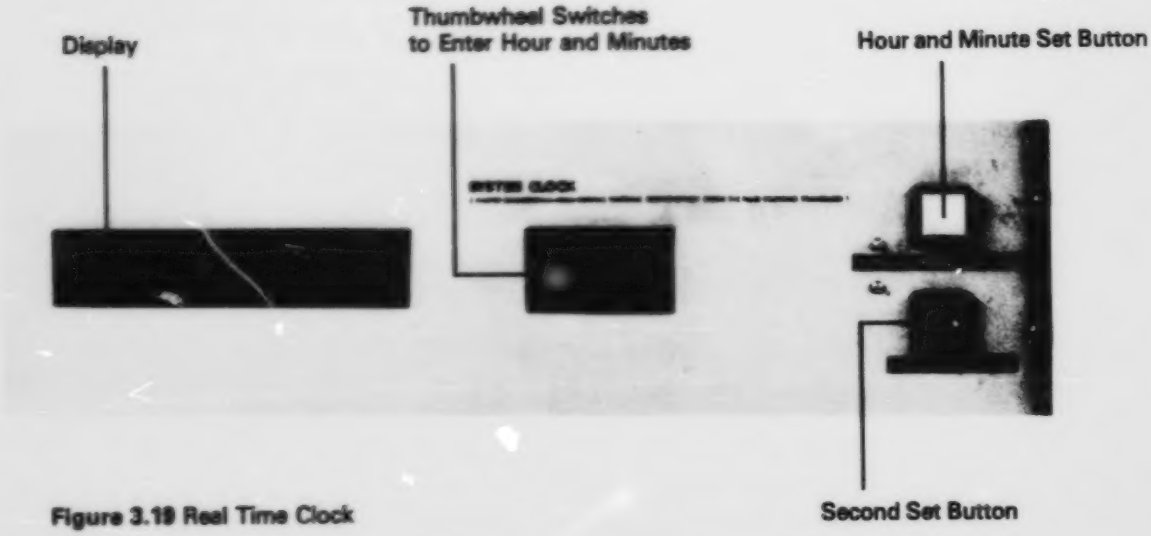


Figure 3.19 Real Time Clock

Front panel controls
Power switch
To energize the unit turn the power switch to its ON position. The switch is located on the rear of the Statistical Multiplexer (See figure 3.18).

Console switch
Is normally set in the OFF position. Channel 0 now operates as one of the asynchronous channels.

System restart
The SYSTEM RESTART pushbutton may be used to manually restart the system. The system should be restarted if the SYSTEM RUN indicator is OFF.

Note: During a restart, any user data held in the buffers will be lost.

Channel select
The CHANNEL SELECT switch should normally be in the "0" position. This sets channel 0 as the monitored channel for the TxData and RxData indicators.

Front panel indicators
Normal indications:

CONSOLE ENABLED	OFF
LINK DCD	ON
LINK ERROR	Will flash occasionally, indicating retransmission due to error. Even on a bad link it should not flash more than once or twice per minute.
LINK RxTx	Will flash according to data activity on the synchronous link, when the link is up.
LINK UP	ON
AUTO RESTART ACTIVE	OFF
TEST ON	OFF
TEST FAIL	OFF
TRAFFIC HEAVY	Will flash occasionally according to buffer loading.
TRAFFIC LOST	OFF
SYSTEM RUN	ON

3.1.4.7 Real time clock

The clock should be checked occasionally for accuracy. To reset the clock, dial in the correct hours and minutes in the 24 hour format with the thumb wheel switches and press the top HOUR AND MINUTE RESET (yellow) button. To reset the seconds to zero press the bottom SECOND RESET (red) button. If a power failure causes a clock memory loss, the two buttons will light up and a time reset is required. The correct time can be monitored on a shortwave radio at 2.5 MHz, 5 MHz, 7.335 MHz, 10 MHz, 15 MHz or on an AM radio tuned to a CBC station.

3.1.4.8 Remote data transmission system (EMSC)

Transmit unit controls
Power
To energize the unit turn the power switch to its ON position. The POWER switch also actively resets the system.

Display
Each press of the DISPLAY button changes the transmitted data and display line. There are twelve distinct transmit and display modes.

Typical displays are:

CZ	EL:XXX.XX'	AZ:XXX.XX'		HH:MM:SS
SZ	EL:XXX.XX'	AZ:XXX.XX'		HH:MM:SS
SCDR	EL:XXX.XX'	AZ:XXX.XX'		HH:MM:SS
EL	C:XXX.XX'	S:XXX.XX'	A:XXX.XX'	HH:MM:SS
CZ	EL:XXX.XX'	ERROR:ACET		HH:MM:SS

Abbreviations:

CZ	= C-Band reflectivity
SZ	= S-Band reflectivity
SCDR	= S-Band circular depolarization ratio
AZ	= Auxilary reflectivity
A	= Auxiliary
EL	= Elevation
AZ	= Azimuth

Error codes:

A	= Azimuth not changing
C	= Communication error
E	= Elevation not changing
T	= Time not changing

DIAG
While holding DIAG button in, press and release RESET, then release DIAG. This will put the system in the diagnostic mode. A second press of the DIAG button will test the display only. In the diagnostic mode the microprocessor in the EMSC unit will sequentially SCAN each section of the unit indicating any errors found. Press RESET to return to transmit mode.

Reset
The RESET button restarts the internal microprocessor. The RESET button will also return the unit to the first transmit and display mode. The first display line is: CZ EL:XXX.XX' HH:MM:SS.

Hr Min Sec
Pressing and releasing these buttons will sequentially advance hour, minutes, seconds allowing the clock to be set to any desired time. Holding any of the buttons down will cause that particular time to advance continuously. Normal display updates stop when these controls are used.

Set
Sets the indicated time. If the set button is not pressed within 60 seconds after the last time update switch is pressed the system will revert to the previous time.

Receive Unit Controls
Power
To energize the unit turn the power switch to its ON position. The POWER switch also actively resets the system.

DIAG
Operated same as transmit unit. Since this system is a one way link, the transmit unit does not indicate when the receive unit is in this mode.

Reset
Used to return to receive mode when in the diagnostic mode.

Receive unit display
The display will show the band selected, elevation, and error codes which are generated by the transmit unit. Only the following displays will be shown depending upon selection of the transmit unit.

CZ	EL:XXX.XX'	ERROR:ACET	HH:MM:SS
SZ	EL:XXX:XX'		HH:MM:SS
SCDR	EL:XXX.XX'		HH:MM:SS
AZ	EL:XXX.XX'		HH:MM:SS
A	EL:XXX.XX'		HH:MM:SS

The receive unit will display TRANSMIT UNIT IN DIAGNOSTICS when the transmitter is in the diagnostic mode.

3.1.4.9 Test receiver (Ailtech)

The Precision Test Receiver is a tuned 30 MHz receiver designed for precise measurements of power level changes by means of the "direct IF attenuation substituation" method. It is used for the isolation checks of the S-Band antenna and the S-Band Phase Discriminator.

Specifications

Input frequency	30 MHZ
3dB bandwidth	1 MHz nominal
Maximum input power	1 watt
Full scale sensitivity	-90 dBm
Input impedance	50 ohm nominal

Operation (IF substitution method)
To operate the Ailtech 13611 follow these steps (refer to figure 3.21).

1. Turn POWER switch to ON position and allow 10 minutes for stabilization.
2. Set the following controls:

MODE	XTAL/DET	DET
DET	NORM/EXP	NORM
+28v	OFF/ON	OFF
3mA	-/+	don't care
XTAL	#1/#2	don't care

3. Connect 30 MHz signal to the input and establish a reference signal level by adjusting the ATTENUATOR control knob for a reading of 50 on the meter. Note the attenuator dial reading.
4. Change the input signal by inserting a device having an unknown attenuation into the system. e.g. Switch the PORT SELECTOR from PORT 1 to PORT 2.
5. Readjust the ATTENUATOR control knob for the original reference level of 50. The difference of attenuator settings between step 3 and step 5 is equal to the attenuation inserted.

Note: All readings should be approached using the same direction of rotation of the control knob to eliminate any antibacklash in the mechanism.

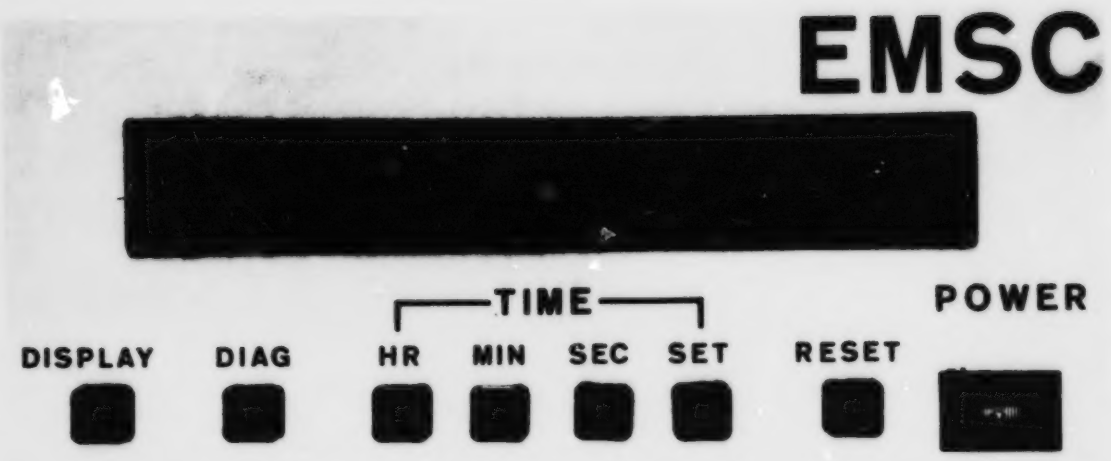


Figure 3.20 Remote Data Transmission System

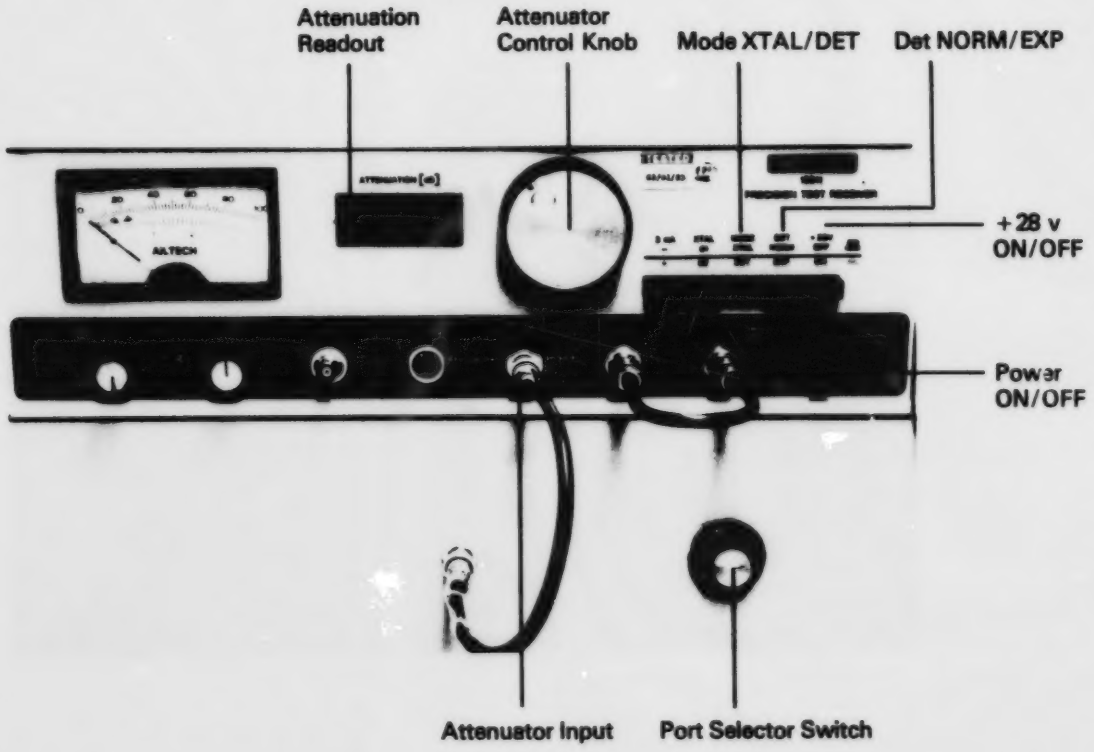


Figure 3.21 Ailtech precision test receiver model 13611

3.2 Measurement and test equipment

In this section instructions for the operation of measurement and test equipment are given. Essentially this illustrates the operation of the following types of instruments:

1. Multimeters
2. Power meters
3. Power supplies
4. Oscilloscopes
5. Waveform generators
6. Frequency counters
7. Synthesized signal generator
8. Spectrum analyzers
9. Wavemeters

3.2.1 Basic

3.2.1.1 Multimeters

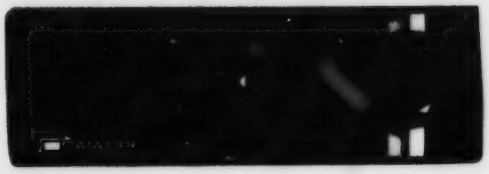
Multimeters are important tools in an electronics lab. There are four digital multimeters in the radar trailer : Fluke Model 8000A (AR0095), Dana Model 3800A (AR0026), Data Precision Model 245 (AR004), Fluke Model 8050A, and one moving coil meter. They are shown in figure 3.22.

Digital multimeters (DVM's) are common place today. With advanced designs, these multimeters have become less supsectible to accidental damage than moving-coil meters (VOM,s). With no moving parts the readability and accuracy of DVM's is superior to VOM's. Probe polarity is no longer significant when measuring voltage or current. But they are still subject to damage through misuse or abuse.

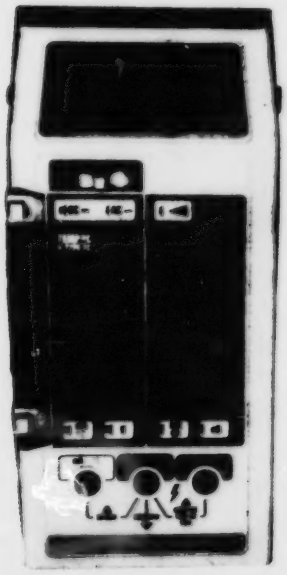
Rules of precaution

All Multimeters generally measure the following parameters: DC/AC voltage, DC/AC current and DC resistance. Operation of different multimeters models is straight forward, therefore, a separate discussion of each meter will not be given. There are however, rules to be followed when using a multimeter regardless of make, model or type.

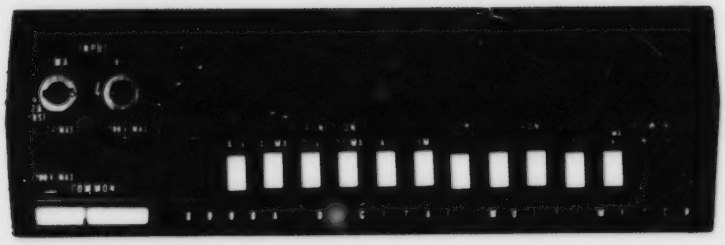
1. When making measurements use the left hand rule, so called because most persons are right handed. Put your left hand in your pocket or behind you back. Clip the test probes to the points of the circuit to be measured with your right hand. In this manner, should a mishap occur, you are not in a position to have current flowing through your left hand, left arm through your chest, and back out your right arm and hand.
2. Always check setting before making a measurement. Start from the highest range setting and work down to the lowest range setting.
3. Voltage measurements are always made in parallel to the device under test. Current measurements are always made in series with the circuit under test.
4. Resistance measurements should be taken on de-energized circuits.
5. The multimeter or its fuse may be damaged if voltage readings are taken on current or resistance settings.



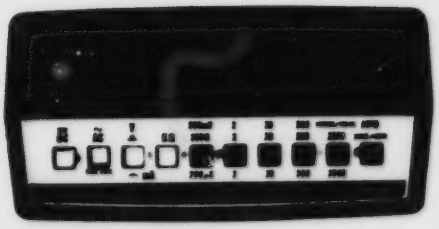
Data Precision Model 245



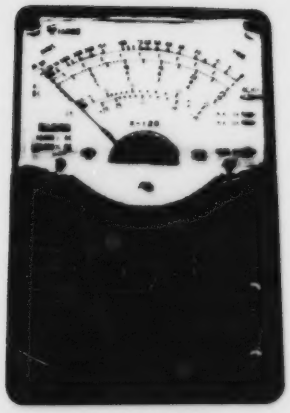
Fluke Model 8024A



Fluke Model 800A



Fluke Model 8040A



Tenco Model X-120

Figure 3.22. Multimeters

3.2.1.2 Power meters

Microwave power meters or power monitors as they are sometimes called, are used to measure RF power levels. They are required because direct voltage measurements at high frequencies are extremely difficult, if not impossible. Most power meters provide a matched load to the power source by the way of a power sensor. Power sensors measure either the heating value of the RF Power received across a thermocouple or by measuring the detected voltage across a crystal diode.

There are two power meters on the radar site, Hewlett Packard Model 435A (AR0099), and Hewlett Packard Model 436A. The Hewlett Packard power meters are able to accept different models of power sensors. There are 2 Hewlett Packard sensors in the lab. One, a model 8481A (AR0086) which uses a thermocouple sense element, and the other, a model 8484A (AR0086) which uses a crystal diode as the sense element.

After measuring the average power, the peak RF power can be calculated using the formula below. Rectangular pulses are assumed.

$$\frac{\text{Average Power Measured}}{\text{pulse width} \times \text{pulse repetition freq.}}$$

Specifications

Power meters are highly susceptible to burn out by excessive input power. There are generally two safety limits, average power limit and peak power limit. Both limits must be strictly observed to protect the power sensor head. Always calculate both the peak and average power levels before connecting the detector. Both limits must be strictly observed to protect the power sensor head. Special care must be used when using model 8484A as it is a highly sensitive sensor, and can be damaged by the power meter's calibration signal.

Input specifications of power sensors

Power sensor	8481A	8484A
Average power maximum	25 dBm (0.3 W)	23 dBm (0.2 W)
Peak power maximum	42 dBm (15 W) (at 2 microsec duration)	23 dBm (0.2 W)
Power range useable	-30 dBm (1 μW) to 20 dBm (100 mW)	-70 dBm (-1n W) to -20 dBm (10 μW)
Frequency range	10 MHz to 18 GHz	10 MHz to 18 GHz

Note: When using the 8484A power sensor it must be calibrated with a attenuator. A 50 MHz reference attenuator, Hewlett Packard Model 11708A, is supplied for this purpose. It has an attenuation of 30dB in order to lower the power reference output to a safe level.

3.2.1.2.1 Hewlett Packard 435A

Operation of Hewlett Packard meter model 435A (AR0099) and Power Sensor Model 8481A (AR0086). Refer to figure 3.23.

1. Turn power on.
2. Zeroing of the meter is achieved by pressing the zero button on the CAL FACTOR switch with the RF source removed and the meter on the most sensitive scale. Allow 5 seconds for the meter to settle to zero.
3. An internal 50 MHz power reference is provided to calibrate the meter. Set CAL FACTOR to 100 percent and select 1 mW full scale setting. Connect the power sensor to the POWER REFERENCE output and turn on the REFERENCE SOURCE with the switch on the back panel.

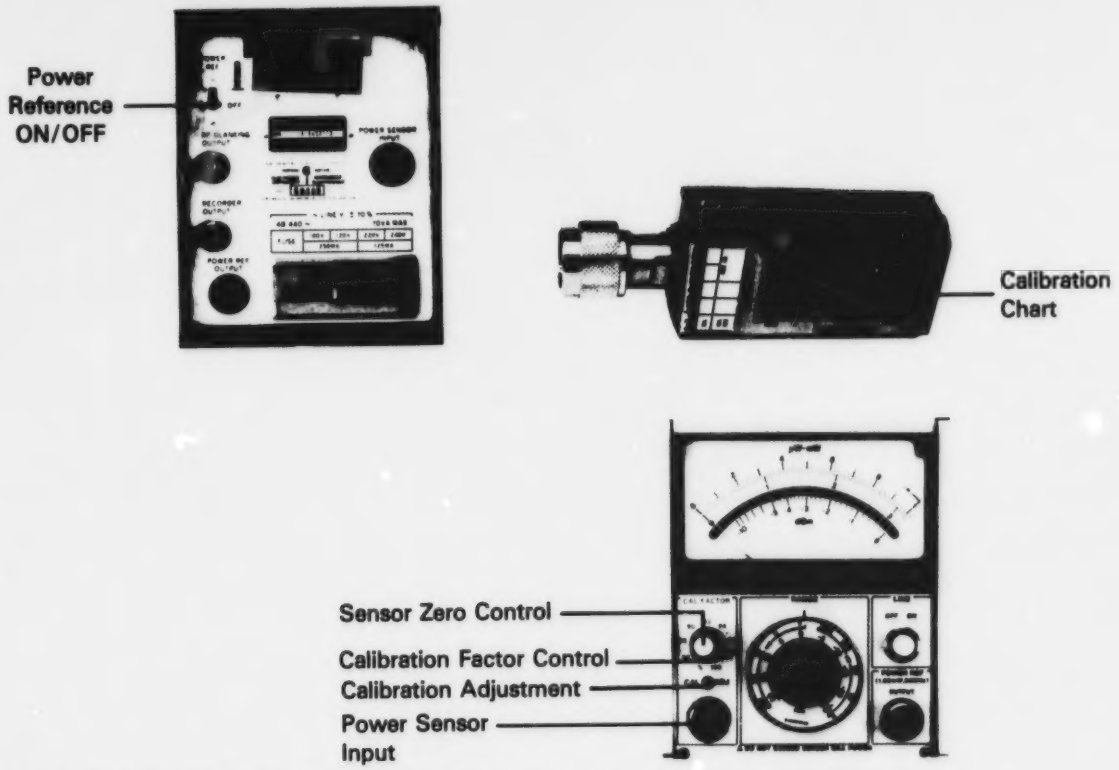


Figure 3.23. Hewlett Packard power meter model 435A and power sensor model 8481A

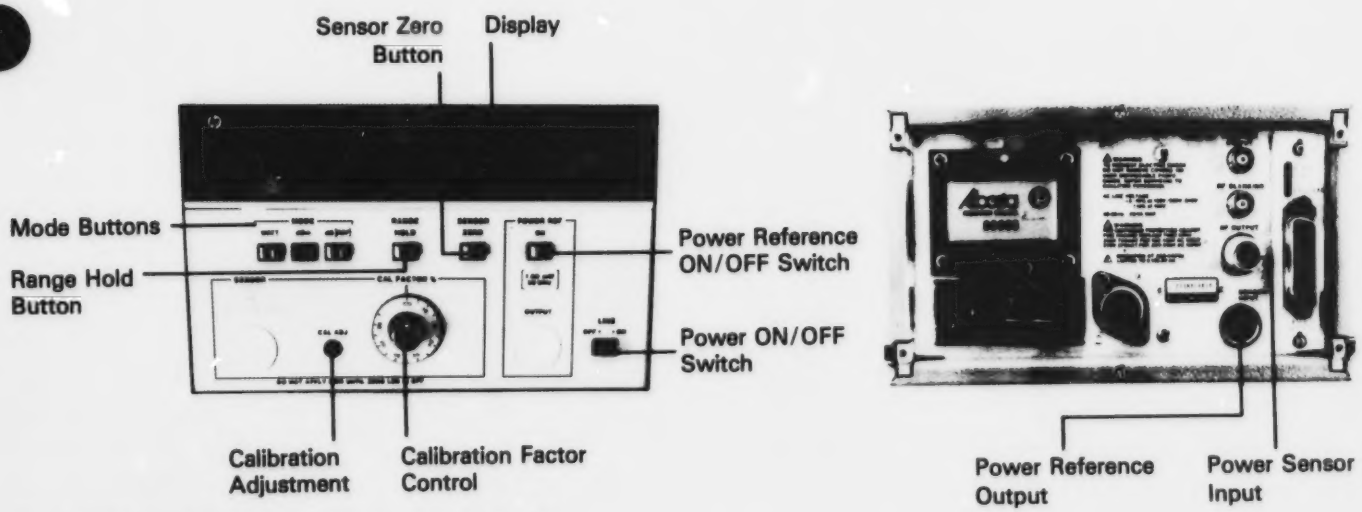


Figure 3.24. Hewlett Packard power meter model 436A

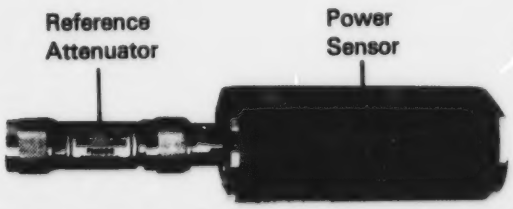


Figure 3.25. Hewlett Packard power sensor model 8484A and 50 MHz reference attenuator model 11708A

4. If necessary, adjust the CAL ADJ potentiometer on the font panel for a meter reading of 1.00 mW full scale.
5. Set CAL FACTOR to optimum position as read off the sensor head, for the desired frequency of operation.
6. To use other power sensors the Range Knob Indicator Plate must come off and a new Range Indicator Plate must be installed. Replace the Range Indicator Plate with the new one making sure the indent and the slot are lined up. Refer to the note on the 8484A for special instructions on calibrating that power sensor.

3.2.1.2.2 Hewlett Packard 436A

Operation of the Hewlett Packard Model 436A is similar to the 435A except for the following: (refer to figure 3.24)

1. Model 436A has the capability of either "Autoranging" or with the RANGE HOLD button pressed in, it will lock the power meter to the last range enabled during the AUTORANGING mode. Our normal mode of operation shall be autoranging thus the RANGE HOLD button should be in the OUT position.
2. To zero the power sensor head press the WAIT Mode button in. Next, press and hold the SENSOR ZERO button until the digital readout stabilizes at 0.00 μW. Verify that the ZERO lamp is lit. Release SENSOR ZERO button and verify that the ZERO lamp remains lit for approximately 4 seconds. When ZERO lamp goes out the digital readout should read 0.00 μW ± 0.02 μW.
3. To calibrate the power sensor, connect the power sensor to the POWER REFERENCE connector and press the POWER REF button. The power meter will autorange to read 1 mW. If nescesary, adjust the CAL ADJ potentiometer for a reading of 1.000 mW.
4. Set POWER REF switch to the OFF (out) position and disconnect the power sensor from the power reference.
5. CAL FACTOR % is adjusted the same way as model 435A.
6. Model 436A has the capability of automatically recognizing the different power sensors and their sensitivities. It will automatically control the digital display decimal point location and light the appropriate power unit display.

Note: When calibrating the 8484A power sensor it must be connected to the power reference through an attenuator. A 50 MHz reference attenuator, Hewlett Packard model 11708A, is supplied for this purpose. It has an attenuation of 30 dB and lowers the power reference output to a safe level for calibration.

3.2.1.3 Power supplies

There are three models of power supplies used in the radar lab for general purpose maintenance. Hewlett Packard Model 6205B (AR0012), Hewlett Packard Model 6285A (AR0011), and the Anatek Model 25-2.0D (AR0036).

All three power supplies are voltage regulated and current limited. The power supplies will maintain a constant output voltage until a current limit is reached. They will then maintain this presetable current limit until the load impedance is increased or removed. An ideal regulated voltage versus current relationship is illustrated in figure 3.26.

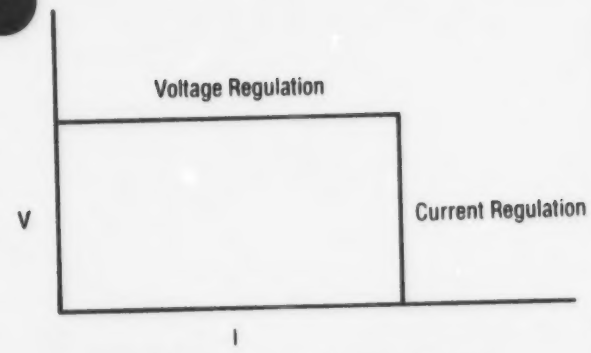


Figure 3.26. Ideal regulated power supply — voltage versus current characteristics

Anatek Model 25-2.00

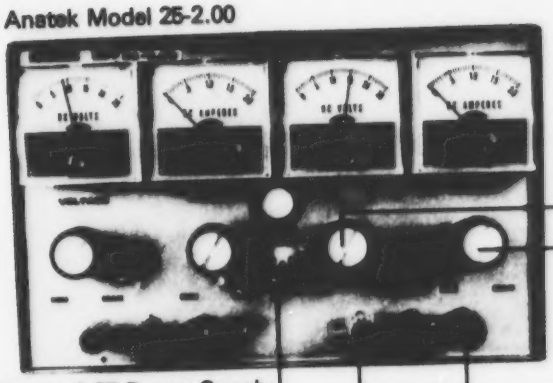


Figure 3.27 Power Supply

Hewlett Packard Model 6285A

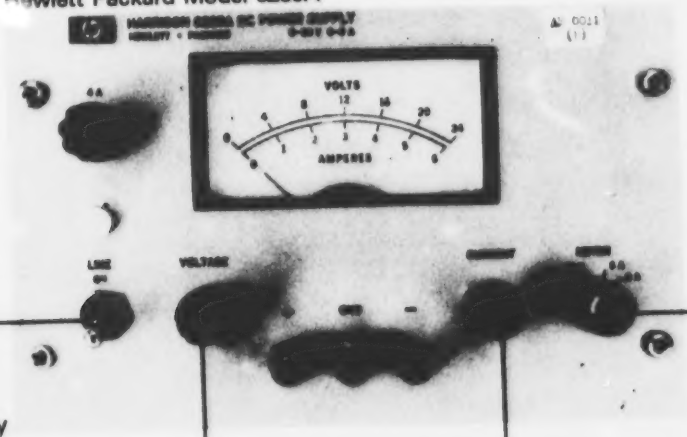


Figure 3.27 Power Supply

Hewlett Packard Model 6205B

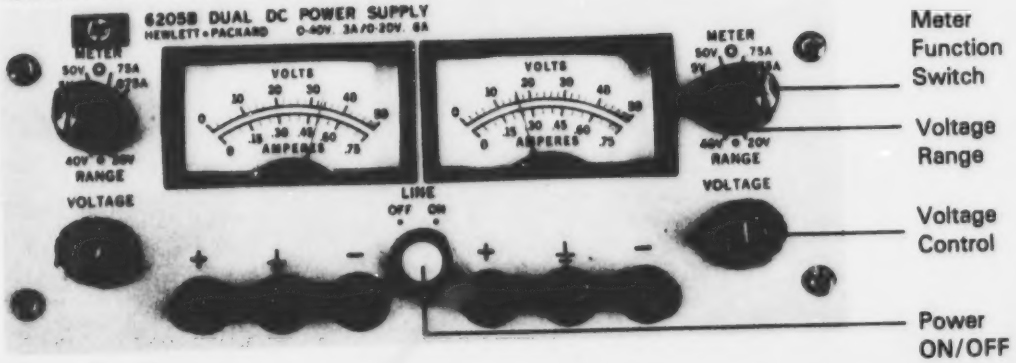


Figure 3.27 Power Supply

Output Specifications Of Power Supplies

Model	Maximum Outputs Voltage (Volts)	Current (Amperes)
Anatek 25-2.0D	25	2.0
Hewlett Packard 6205B	40	0.3
	20	0.6
Hewlett Packard 6285	20	5.0

To operate, simply set the power supply to the desired voltage level by adjusting the voltage level control and reading a multimeter that has been connected to the output of the power supply. If the current limit is to be preset for a particular load, short the power supply output and adjust the current limit control to the desired level as read on the current meter. The Hewlett Packard Model 6205B does not have a variable current limit setting. Connect the power supply to the load, making certain that the polarity is correct.

3.2.2 Time domain

3.2.2.1 Oscilloscopes

A tutorial on the operation of oscilloscopes called "XYZs of using a scope" is available for perusal in Appendix B-II-i. This document is recommended for those unfamiliar with oscilloscope operation.

3.2.2.1.1 Hewlett Packard 1703A (AR0013)

The model 1703 A is a lightweight portable dual trace scope capable of measurements up to 35 MHz and with the additional capability of storing traces on the CRT.

Very slow or nonrepetitive signals are difficult to observe on a oscilloscope, with a storage scope this problem is minimized. To store a trace, obtain a clean, stable trace in standard mode. To put the scope in the storage mode, depress on of the writing speed buttons, normally standard writing speed. Adjust the intensity control to a level at which the trace does not bloom. Adjusting the variable persistence control will determine the length of time the trace will remain on the face of the CRT, without fading. In continuous sweep, the sweep will overlay the previous one causing the display to bloom and smear. Decreasing the intensity will minimize this.If the display becomes unreadable before fir.al adjustments can be made, erase the screen by pressing the erase button located in the middle of the presistence control. Once the desired trace is displayed on the CRT it can be stored, no other traces will be superimposed on the screen. To store the display, press the store button. Adjust the store time for the desired time, normally midway is sufficient. You now have a frozen and stored display for analysis. To store another trace, press one of the write speed buttons and erase the screen and repeat the procedure.

3.2.2.1.2 Tektronix 475

The model 475 is a lightweight portable dual trace scope equipped with a detachable battery pack and is capable of measurements up to 200 MHz.

3.2.2.1.3 Tektronix 7403N (AR0017, AR0018 and AR0020)

Model 7403N is a general purpose portable oscilloscope that is used for general maintenance of equipment in the radar trailer. The 7403N includes two Dual Trace Amplifiers (7A18A) with a bandwidth from DC to 75 Mhz. It also includes a Dual Time Base (7B53A) that can be triggered up to 100 Mhz.

Note: This and other Tektronix oscilloscopes have replaceable modules that have different functions and specifications from each other. Be sure your oscilloscope has compatible modules for the intended use.

3.2.2.1.4 Tektronix R7603 (AR0127)

Model R7603 is a rack mounted oscilloscope that includes 2 Dual Trace Amplifiers (7A26) with a bandwidth up to 200 MHz and a Dual Time Base (7B53A) with a triggering capability up to 100 MHz. It is used as our main calibration and general purpose scope.

3.2.2.2 Waveform generators

There are many types of waveform generators available today capable of generating waveforms such as squarewaves, sinewaves, triangular waves, and pulses, to name a few.

The waveform generators in the lab are used in calibration of the radar systems and for general maintenance.

3.2.2.2.1 Dana Exact 516

This is a versatile pulse/sweep function generator for general use in the laboratory.

Specifications

Frequency Range	.01 Hz to 11 Mhz
Output Voltage	10 V peak to peak into 50 ohms

When using this generator, be careful not to short circuit the output. Operation of the generator is listed below: (Refer to figure 3.32)

Pulse modulation

1. Set MODE control to TRIG, OFFSET button to in, FUNCTION control for a positive squarewave, FREQ RANGE control as appropriate and START FREQ outer knob to S (search).
2. Connect OUTPUT to oscilloscope and system trigger to TRIG IN connector. Scope should also be externally triggered by system trigger.
3. Adjust START FREQ inside knob and START PHASE control to obtain desired pulse width and delay from system trigger.
4. Set OFFSET, ATTENUATOR, and AMPLITUDE controls to obtain desired pulse amplitude.
5. Disconnect OUTPUT from oscilloscope and connect to the circuit under test.

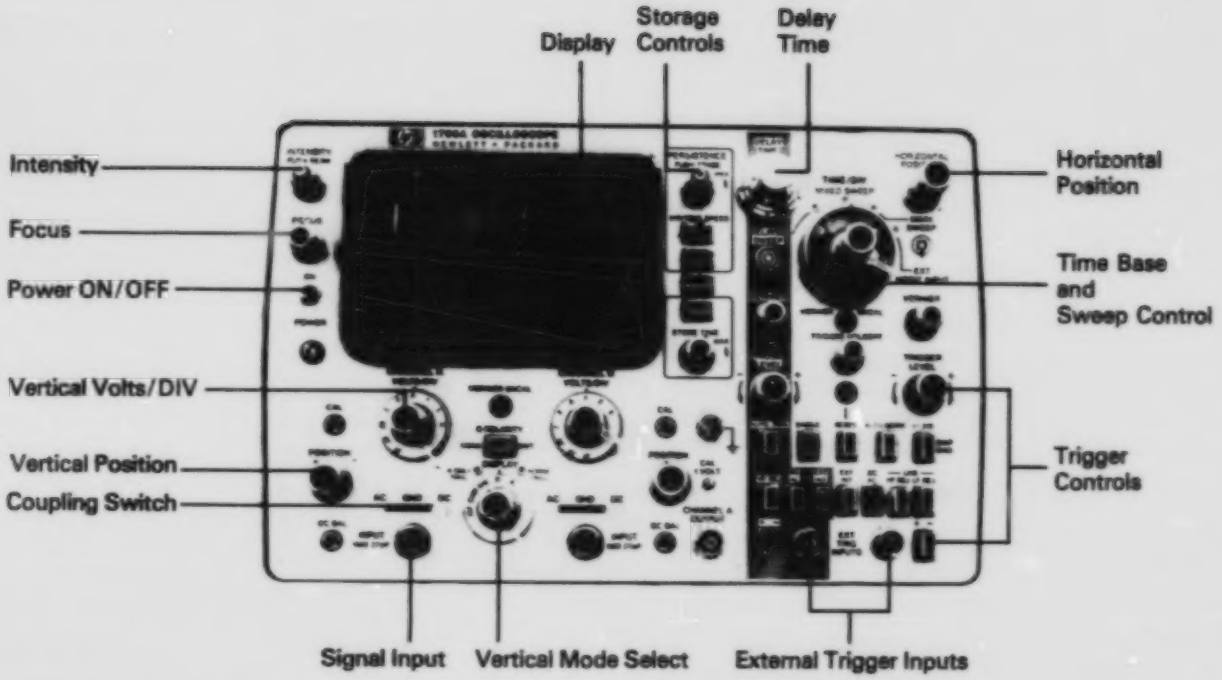


Figure 3.28. Hewlett Packard oscilloscope model 1703A

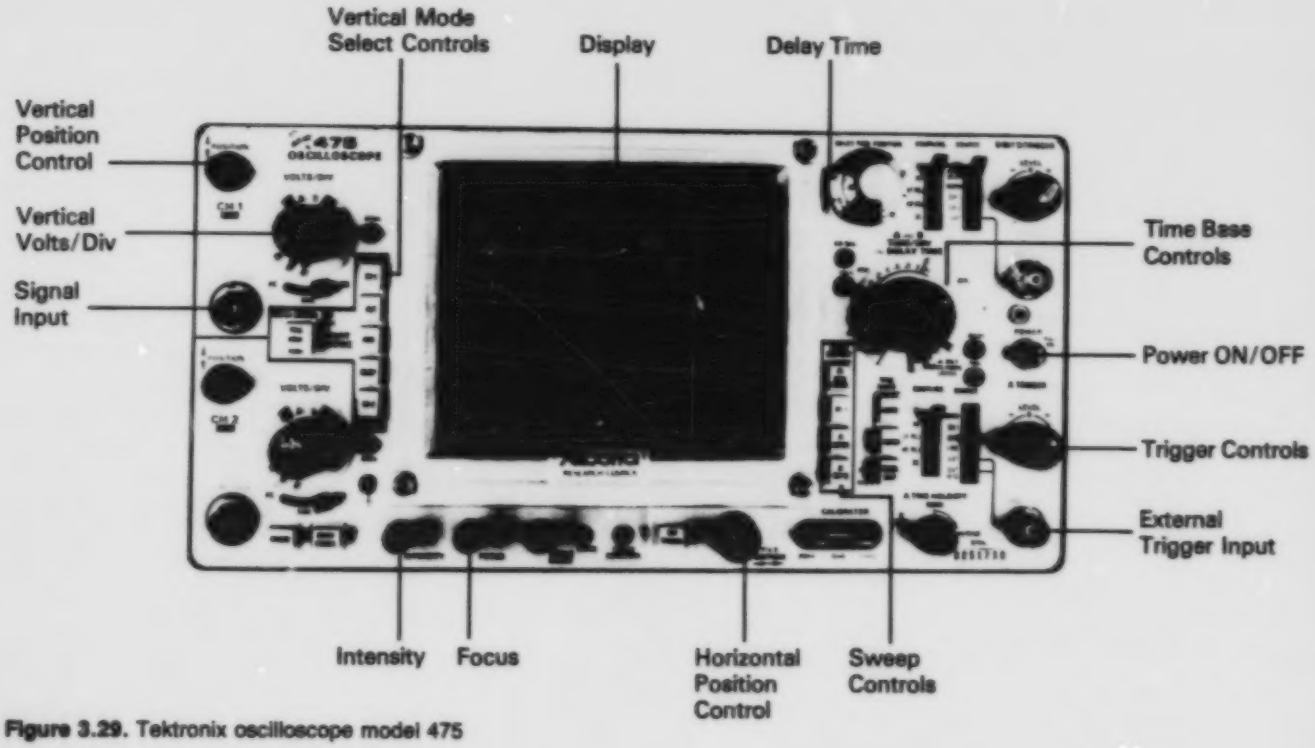
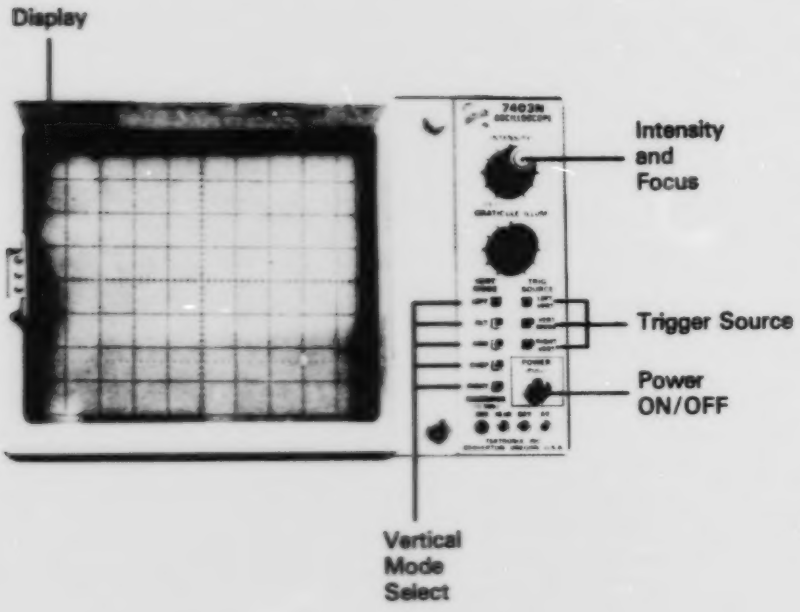


Figure 3.29. Tektronix oscilloscope model 475



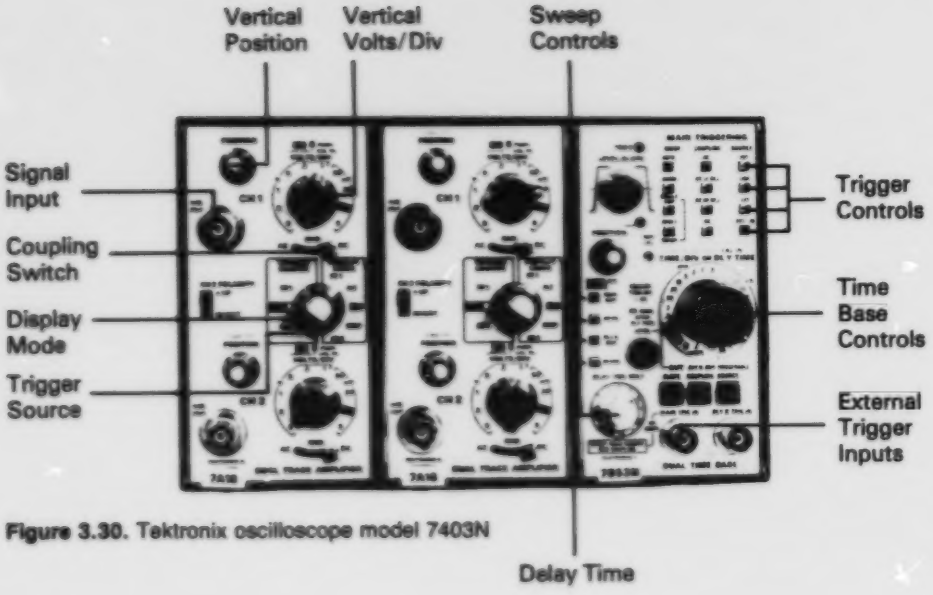


Figure 3.30. Tektronix oscilloscope model 7403N

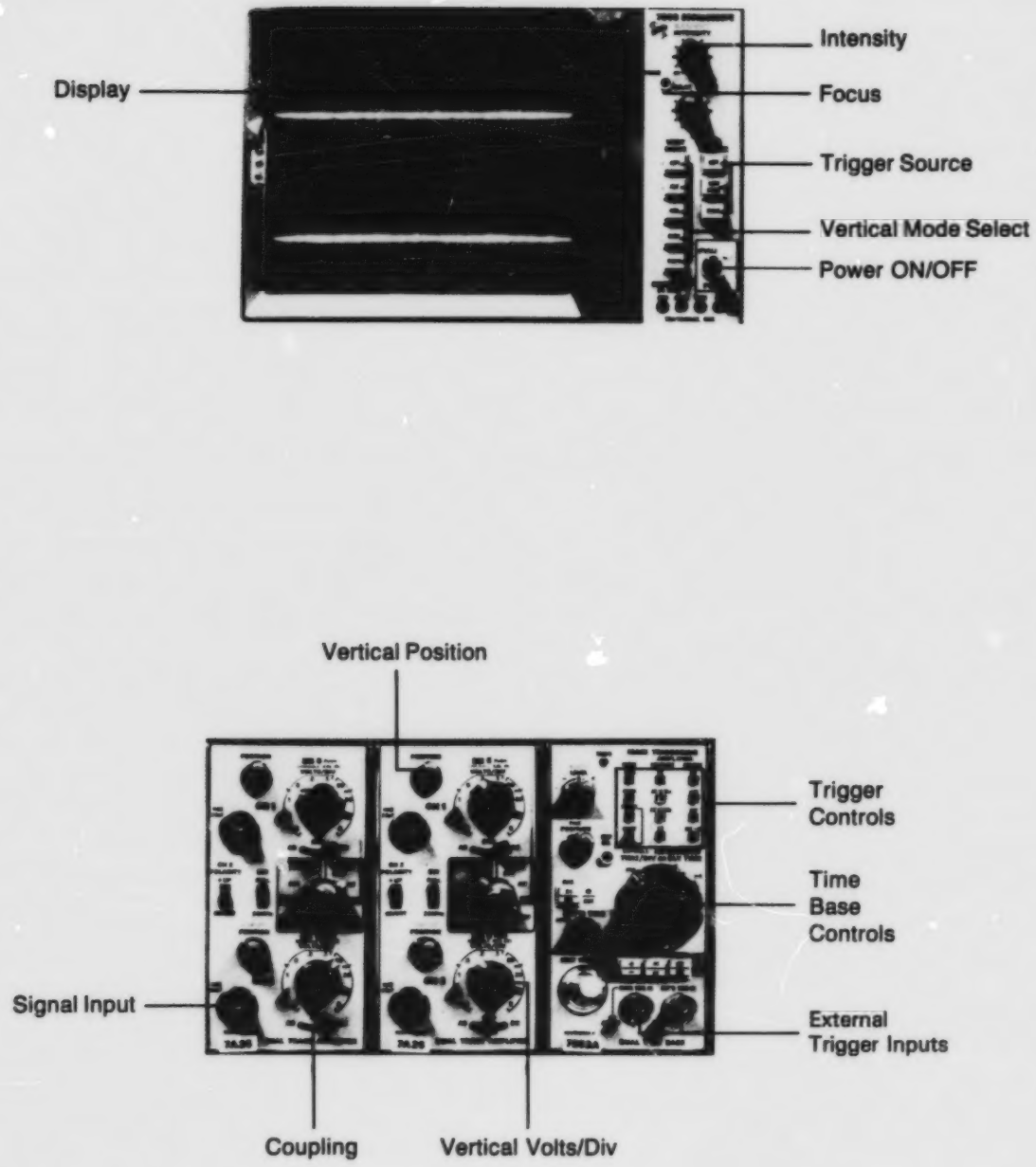


Figure 3.31 Tektronic Oscilloscope Model R7603

3.2.2.2.2 Tektronix 2101

The Tektronix 2101 is a general purpose pulse generator, capable of generating pulses as narrow as 20 ns. It can be used to modulate the Hewlett Packard 8673A signal generator or by itself for general maintenance.

Specifications:

Pulse duration	20 ns to 1 s
Pulse period	40 ns to 4 s
Pulse delay	20 ns to 4 s
Rise and fall time	5 ns or less
Pulse amplitude	300 mv to 10 v peak (with Internal Termination OUT)

Operation (refer to figure 3.33)

Operating instructions are for the DELAYED PULSE mode operation only. For other modes of operation, consult the technical manual.

1. Connect system trigger to the TRIG IN input.
2. Turn POWER switch ON and let instrument warm up for 10 minutes.
3. Set the PULSE MODE switch to the DELAYED position.
4. Set the PERIOD decade selector switch to the EXT TRIG position.
5. Set the NORM-EXT GATE switch to the NORM position.
6. Set the two BASELINE OFFSET switches to the OFF position.
7. Set the two 50 OHM INTERNAL TERMINATION switches to the IN position.
8. Connect an oscilliscope to the positive pulse output of the pulse generator to observe the output waveform.
9. Adjust for the desired pulse width the PULSE DURATION decade selector switch and the variable adjustment control.
10. Adjust the DELAY controls to provide the desired delay.
11. Adjust the pulse amplitude for the desired level with the variable PULSE AMPLITUDE control.
12. Connect output to load.

3.2.3 Frequency domain

3.2.3.1 Frequency counters

A basic frequency counter is used to count frequencies. A more sophisticated model may have the added capabilities of measuring time intervals, periods, events, and duty cycles to name a few.

There are two models of frequency counters in the radar trailer. The Hewlett Packard model 5302A (AR0014) is capable of measuring signals up to 50 MHz. The Hewlett Packard Model 5345A (AR0001) is capable of directly counting up to 500 MHz and with the use of a Frequency Converter Model 5255A (AR0080) is capable of counting from 2.6 GHz to 12.6 GHz. For further information on either of these counters, see Appendix A-II-iii-a.

3.2.3.2 Synthesized signal generator Hewlett Packard 8673A

The 8673A signal generator is used to calibrate the radar systems.

Specifications:

Frequency Range:	2GHz to 26Ghz	
Maximum Output Power:	+7dBm to -100dBm	2.0 GHz to 18.0 GHz
	+2dBm to -100dBm	18.0 GHz to 22.0 GHz
	-2dBm to -100dBm	22.0 GHz to 26.0 GHz

Note: The signal generator is not calibrated for output levels above +7dBm. Spurious oscillations may occur above this level.

Pulse input:	Normal mode:	<0.5 volts OFF, >3 volts ON
	Complement mode:	<0.5 volts ON, >3 volts OFF
	Impedance:	50 ohms nominal
	Maximums:	-0.5 volts peak and +6 volts peak

Operation

To operate the 8673A signal generator in the pulse mode, follow these steps (refer to figure 3.34)

1. For pulse mode operation, a modulating pulse must be connected to the PULSE IN connector on the front panel. The Tektronix 2101 Pulse Generator can be used for this purpose (refer to section 3.2.2.2.2).
2. Set the LINE switch to the ON position and wait for the OVEN COLD status light to turn off.
3. If the MESSAGE key light is on or flashing, press the MESSAGE key once to read the two-digit code in the FREQUENCY MHz display. These codes are explained on the operating information pull-out card.
4. Set the following functions for these indicatings:

RF OUTPUT:	OFF
ALC INTERNAL:	ON
AUTO PEAK:	ON
METER SCALE:	LVL
PULSES IN:	NORM
PULSE OFF:	ON
MKRS:	OFF
SWEEP MODE:	OFF
TUNE KNOB:	ON

5. Set the frequency needed by pressing the FREQUENCY button and then entering the correct frequency and units with the data keys. The frequency can be fine-tuned by using the TUNE knob.
6. To set the step size of the TUNE knob press the FREQ INCR key and input the desired frequency increment with the Data and the Unit Keys.
7. Set the desired output level by first selecting the proper range with the OUTPUT LEVEL RANGE keys that will increment or decrement the range by 10dB. Then adjust the RANGE VERNIER knob over a range of -10 to +3dB, relative to the LVL scale as read on the meter.
8. Press the RF OUTPUT button ON to output the RF signal.

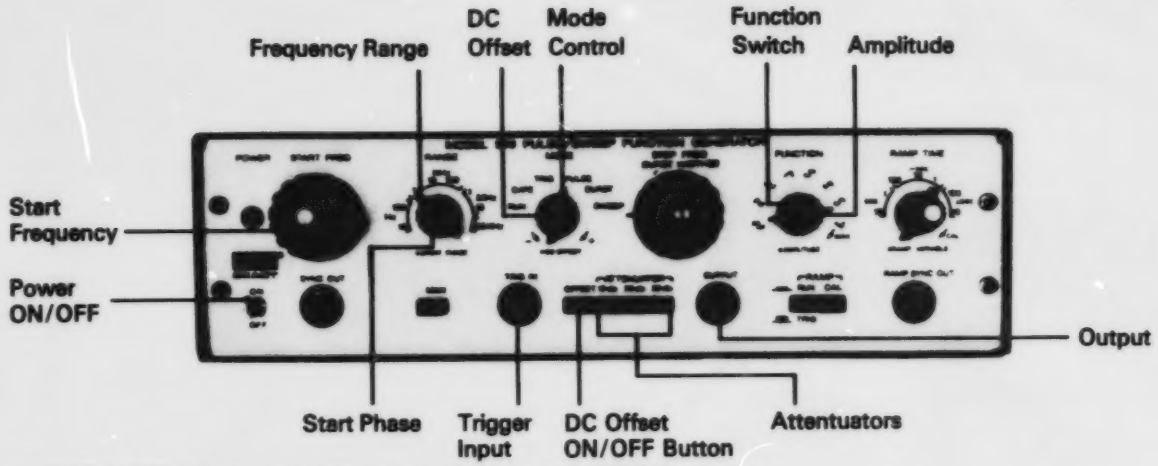


Figure 3.32. Dana Exact pulse/sweep function generator model 516

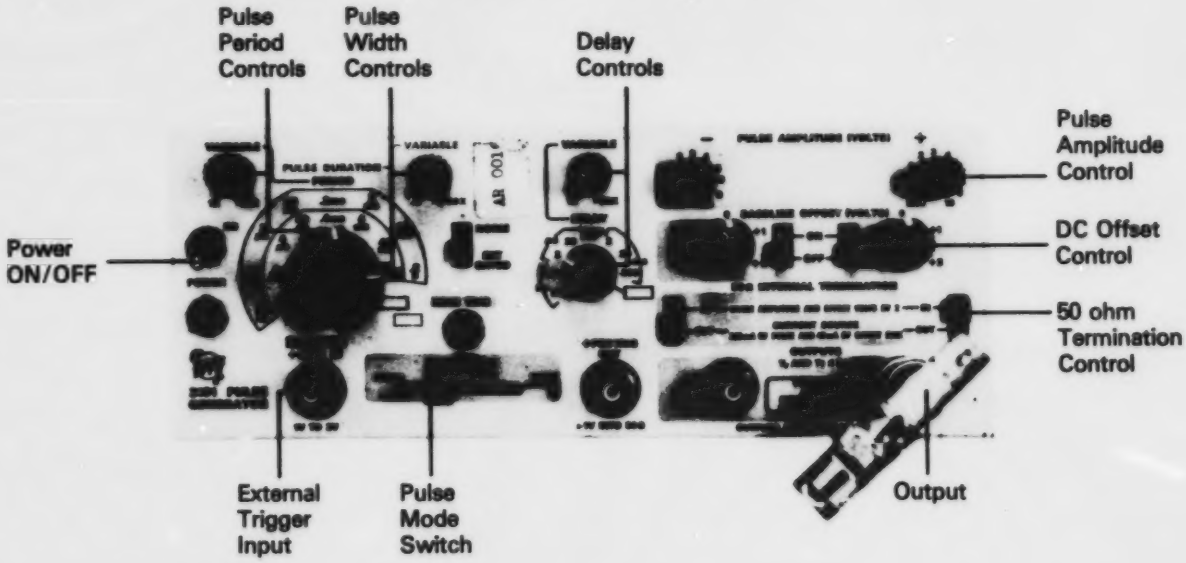


Figure 3.33. Tektronix model 2101 pulse generator

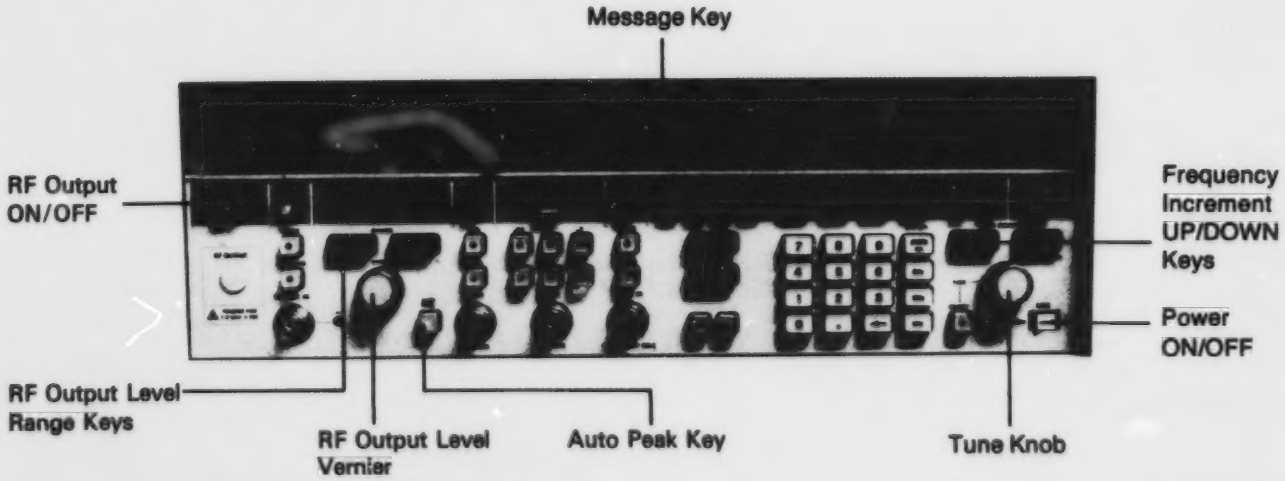


Figure 3.34. Hewlett Packard synthesized signal generator model 8673A

3.2.3.3 Spectrum analyzers

A spectrum analyzer is used to make frequency domain measurements. It is basically an heterodyne RF receiver with a voltage controlled local oscillator. By sweeping the LO frequency, signals in the frequency band can be displayed as vertical signals on a CRT, with the horizontal sweep synchronized to the LO sweep rate. Spectrum analyzers are susceptible to damage by excessive input power. The maximum power ratings for the instrument must be observed and the input peak power must be calculated before RF is connected. Insert extra attenuation, if necessary. An RF limiter is available to safeguard the analyzer against any unexpected RF power surges. This limiter usually generates unwanted harmonics when it is limiting. Spectrum analyzer control signals which exceed input specifications are also dangerous.

3.2.3.3.1 Hewlett Packard 141T

1. Set the following controls on the spectrum analyzer before connecting to the RF Source.

Display section

POWER:	ON
MODE:	NON Storage
INTENSITY:	As required
FOCUS:	As required

IF section

IDEO FILTER:	OFF
SCAN TIME PER DIVISION:	10 MS
SCAN MODE:	INT
SCAN TRIGGER:	AUTO
SCALE:	10 dB LOG
LOG REF LEVEL:	Fully ccw
VERNIER:	0 dB
BASE LINE CLIPPER:	Fully ccw

RF section

FREQUENCY BAND TUNE:	Desired frequency band
FREQUENCY COARSE TUNE:	Desired frequency
FREQUENCY FINE TUNE:	Centre
BAND WIDTH:	300 KHz
INPUT ATTENUATION:	50 dB
SCAN WIDTH MODE CONTROL:	FULL
SCAN WIDTH PER DIVISION:	200 MHz
TUNING STABILIZER:	ON
SIGNAL IDENTIFIER:	OFF

2. Calculate peak power at the RF source. Select appropriate input attenuation. Insert additional attenuators as required. For typical radar peak pulse of 84 dBm (250 kW), and typical coupling factor and attenuation of 70 dB, the minimum input attenuation is 30 dB.
3. Connect RF input to RF limiter.
4. Adjust Focus, INTENSITY, and BASE LINE CLIPPER to obtain optimum trace on screen.
5. Select LOG REFERENCE LEVEL and INPUT ATTENUATOR to obtain a signal above noise on the display.
6. Tune coarse FREQUENCY control to position the marker under the signal of interest.
7. Set SCAN WIDTH mode to PER DIVISION.

8. Reduce SCAN WIDTH PER DIVISION, keeping the signal at the centre of the display by adjusting the frequency tune control.
9. Reduce Bandwidth if higher resolution is required. The display UNCAL light will turn on when the control settings are such that the calibration of the spectrum analyzer is impaired. This warning indicator is associated with bandwidth, scan width per division, SCAN TIME PER DIVISION and the Video Filter Controls. One way to turn this indicator "OFF" is to increase the SCAN TIME PER DIVISION.
10. When SCAN WIDTH PER DIVISION control is set to 1 MHz or less turn on signal identifier to ensure that the signal is not a spurious image. A second signal 2 divisions to the left and lower in amplitude than the original should appear. If necessary, rotate the band switch until the signal is correctly identified. Turn identifier off after use.
11. If SCAN SPEED becomes too slow, then select storage on the display section with STANDARD WRITING SPEED. Adjust PERSISTENCE and INTENSITY to provide a good display.
12. To observe the modulated side band characteristics and frequency information, band width and scan width should further be reduced to improve display resolution.
13. For radar RF pulse studies, the 3 dB band width can be observed by switching the SCALE to the 2 dB LOG position and by measuring the width of the mainlobe at the two 3 dB points below the peak.

3.2.3.3.2 Tektronix 492P

Specifications

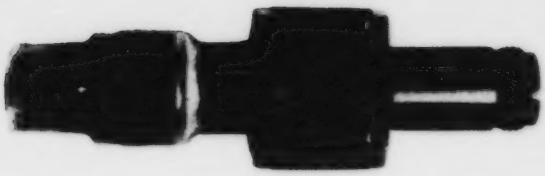
Maximum Input:	+30 dBm with 0 RF attenuation 1 db compression point -18 dBm with 0 db RF attenuation
Frequency Range:	100 KHz to 21 GHz

Start up Procedure

1. Pull the Power Switch to turn the 492P on. A green LED should come on in approximately 1 second and the SPECTRUM ANALYZER will go through a self test routine. The CRT should light up and the apropriate LED will turn on the indicate the following 'Start up' conditions.

FREQUENCY:	0 MHz
VERTICAL DISPLAY:	10 dB/Div
REFERENCE LEVEL:	+30 dBm
RF ATTEN:	60 dB
FREQUENCY RANGE:	0.0 - 1.8 GHz
AUTO RESOLUTION:	ON
RESOLUTION BANDWIDTH:	1 MHz
FREQ SPAN/DIV:	MAX
TRIGGERING:	FREE RUN
READ OUT:	ON
DIGITAL STORAGE:	VIEW A/VIEW B

2. Adjust Intensity control for desired brightness.
3. Allow 5 minutes for instrument to warm up and stabilize.



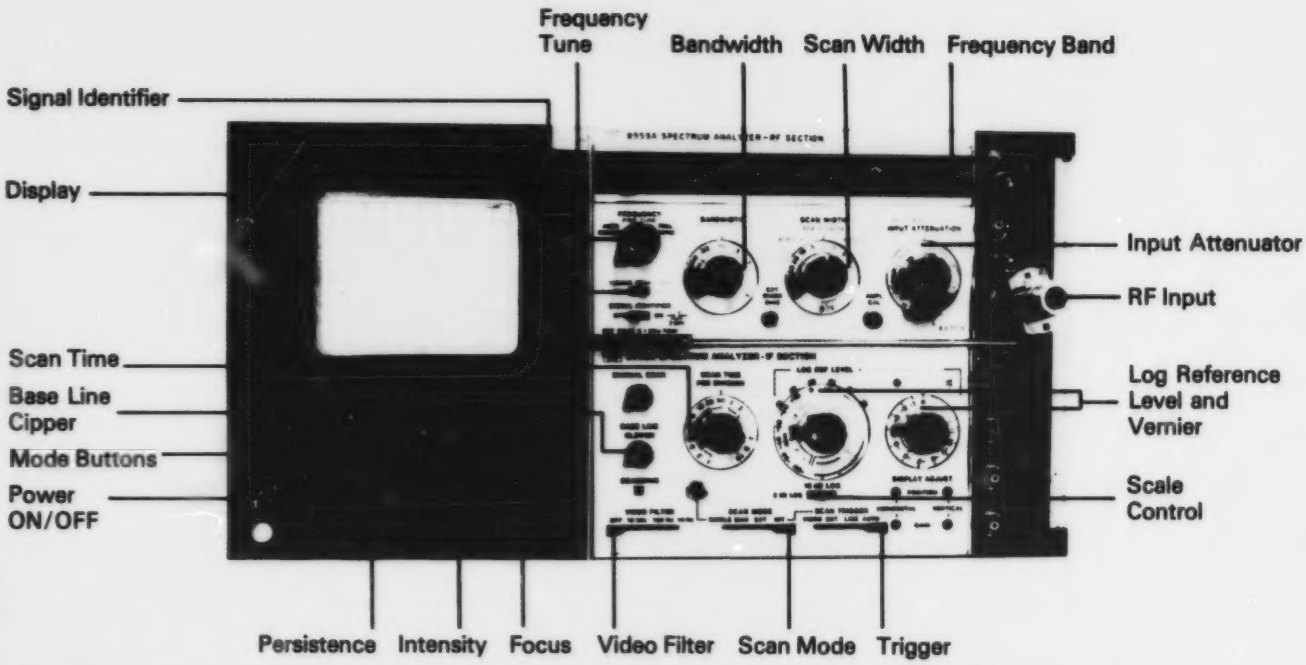


Figure 3.35. Hewlett Packard spectrum analyzer 141T and Hewlett Packard RF limiter model 11693A

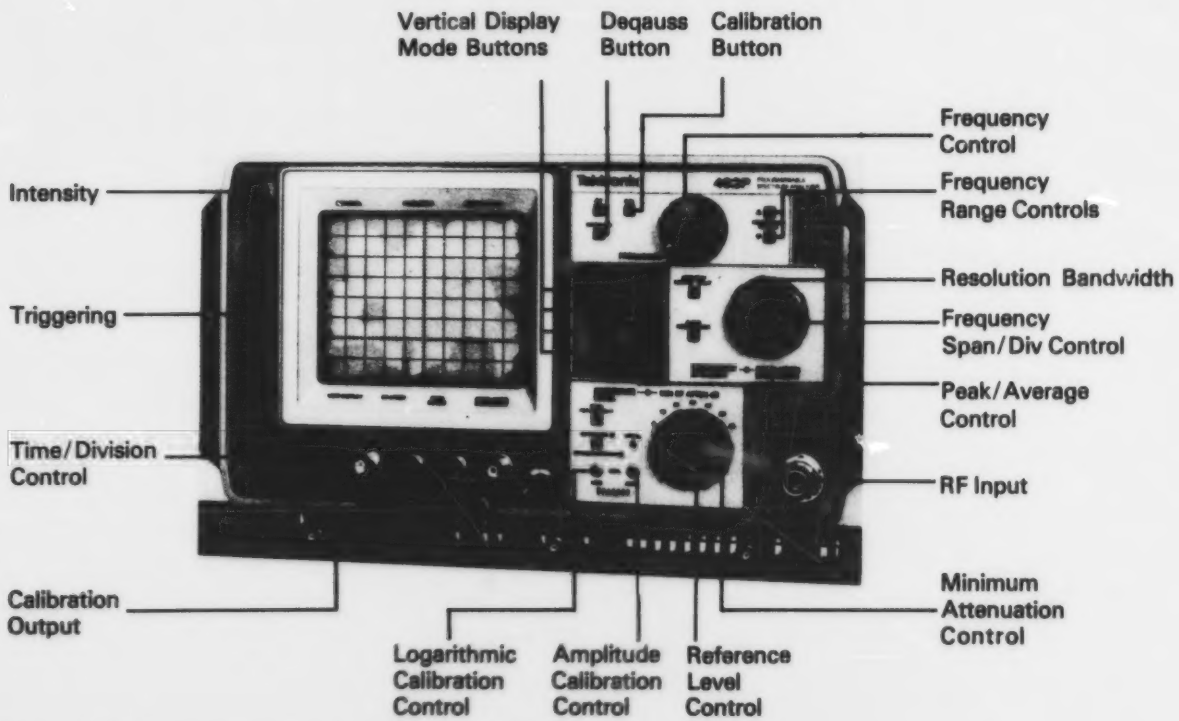


Figure 3.36. Tektronix spectrum analyzer model 492P

Calibration Procedure

It is necessary to calibrate the CENTER FREQUENCY READOUT when first turning the instrument on. It is also necessary to DEGAUSS the tuning coils for a center frequency change of 1 MHz or greater.

1. Set the following controls:

MIN RF ATTEN:	0 dB
PEAK/AVERAGE:	Fully ccw
TIME/DIV:	AUTO
REFERENCE LEVEL:	-20dBm

2. Connect a 50 ohm coaxial cable between the CAL OUT connector and the RF INPUT connector.
3. Adjust the FREQUENCY control to tune in the fist 100 MHz marker pulse by moving the marker dot to a position above the first 100 MHz marker pulse.
4. Change the FREQ SPAN/DIV to 100 MHz. The marker dot should now be centered horizontally and the 100 Mhz signal near the center of the display.
5. Readjust the FREQUENCY control to place the 100 MHz marker over the marker dot.
6. Reduce the FREQ SPAN/DIV control to 1 MHz.
7. Press the DEGAUSS button and at the same time fine tune the 100 MHz marker pulse to the center graticule, by using the FREQUENCY control knob. **Note:** DEGAUSS function is inoperative when the FREQ SPAN/DIV is less than 1 MHz.
8. Press the CAL button. Adjust the FREQUENCY tuning control for a readout of 100 MHz.
9. Press the CAL button again to deactivate the calibration function.
10. Increase SPAN/DIV to 20 MHz.
11. Check the center frequency accuracy at multiples of the 100 MHz signal. Approach each check point from the low frequency side and DEGAUSS the tuning coils of the oscillator as each check point is approached. The readout should be within ± (5 MHz + 20% SPAN/DIV) or ± (.2% of center frequency + 20% SPAN/DIV) whichever is greater.

To calibrate or check the REFERENCE follow this procedure:

12. With the 100 MHz calibrator signal tuned to center screen and the REF LEVEL at -20 dBm, set the FREQ SPAN/DIV to 20 KHz.
13. Alternately switch the VERTICAL DISPLAY from 10 dB/DIV to 2 dB/DIV and adjust AMPL CAL so that the peek amplitude is the same for both displays.
14. With VERTICAL DISPLAY mode at 10 dB/DIV set the top of the calibration signal to the top graticule line by adjusting the LOG CAL potentiometers.

For more complete information on the 492P, consult the reference manual.

3.2.3.4 Wavemeters (frequency meters)

Wavemeters are mechanical cavity resonant devices used to measure the frequency of microwave sources. At resonance, power is absorbed from the transmission line by the wavemeter. If a power monitor is connected to a power source through a wavemeter, a power drop is observed when the wavemeter is tuned to its resonant frequency. At frequencies other than the resonant frequency the least power is absorbed by the wavemeter.

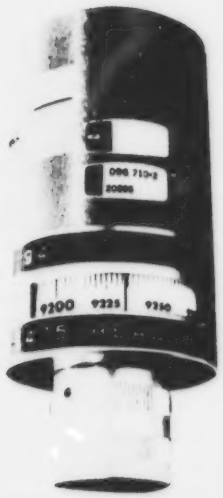
Wavemeters are bi-directional; either connector can be used as input or output. Since wavemeters are mechanical devices, they are susceptible to damage by vibration and shock. Avoid turning the meter knob into the stops at either end of the dial.

There are three wavemeters in the laboratory: FXR model N410A used for S-Band measurements, Hewlett Packard Model 537A (AR0102) used for C-Band and X-Band measurements, and Atelco model DGB710-2 used for X-Band measurements. (Refer to figure 3.37). Both the FXR and the Hewlett Packard Models have type N coaxial inputs. The Atelco has waveguide inputs and is used in the transponder test set.

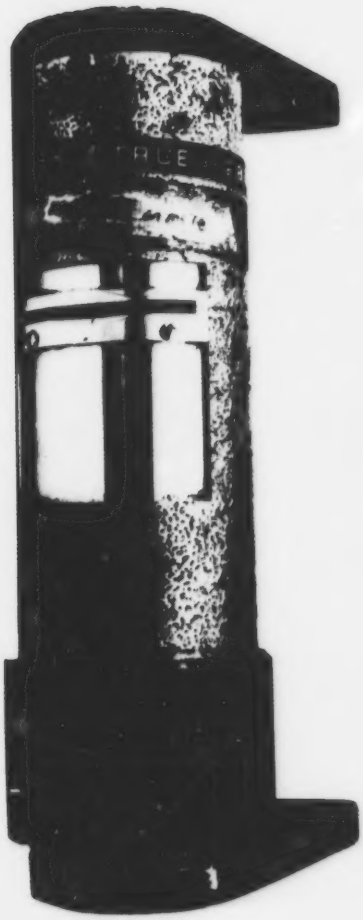
In radar output power and frequency measurements, remember to remove or detune the wavemeter in order to measure true power.

Operation of Wavemeters

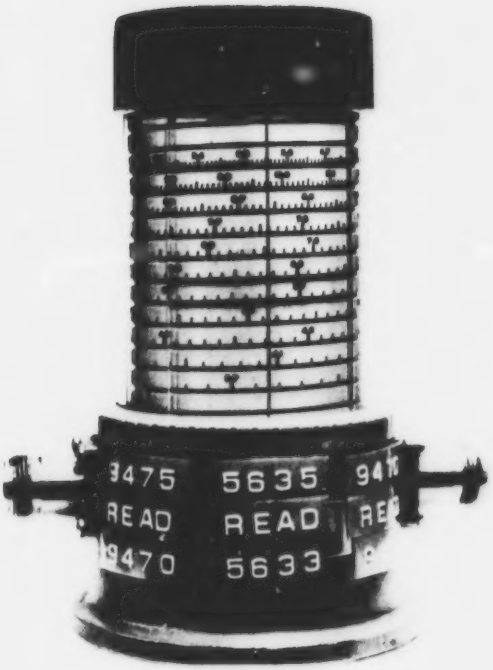
1. Connect a power source to the wavemeter input.
2. Make sure power meter safety rating is not exceeded. See section 3.2.1.2 on the use of power meters. Connect the power meter to the wavemeter output.
3. Adjust the wavemeter until a minimum (dip) in power reading is observed.
4. Maximize the dip by slowly turning the wavemeter dial back and forth.
5. When the position of maximum dip is determined, read the wavemeter dial to resolve the frequency of the power source.
6. Wavemeters should be detuned after a measurement is made to avoid unnecessary power loss or spectrum disturbances at the frequency of interest.



Atelco Model DGB710-2



FXR Model N410A



Hewlett Packard Model 537A

Figure 3.37. Wavemeters

Chapter four: Calibration and system performance checks

4.1 Electronic systems

In this section system performance and operational checks are outlined. Sample calibration charts and checklists are shown in appendix E.

Measuring noise and noisy signals using a multichannel oscilloscope
During calibration of the radar receivers, measurements of noise and noisy signals at the output terminals of the logarithmic amplifiers and range integrators are required. A method of measuring low level noise signals, using a multichannel oscilloscope has been developed and is an integral part of the calibration procedure. This technique results in more consistent calibration values when noise or predominantly noisy signals are being measured. Conventional methods may be used when the signal to noise ratio of the calibration pulse, viewed on an oscilloscope, becomes clean. The criterion for a clean calibration pulse is when the top of the pulse is less than three times the thickness of an unmodulated oscilloscope beam.

To prepare the oscilloscope for the measurement, two oscilloscope vertical input channels are connected to the signal to be measured. One of the vertical input channels is operated in the inverted mode, a positive signal causes a negative deflection of the beam and vice versa. In this manner the normal and inverted forms of the measured signal are simultaneously displayed on the oscilloscope screen. The vertical input to the normal trace is momentarily grounded with the coupling selector switch at GND and the resulting horizontal line is superimposed on the bottom graticule line by using the vertical position control. Upon completion of the alignment, the coupling selector switch is returned to DC and the sensitivity setting is adjusted to bring the displayed signal into the lower half of the screen. The inverted channel must be set to the same sensitivity settings, coupling factors, and its trace located in the upper half of the screen. The measurement can now be performed.

Adjust the inverted waveform vertical position control to clearly seperate the two waveforms. The upper, inverted waveform is moved down toward the lower, normal waveform until the noise on both waveforms begins to merge and the trace takes on a uniform intensity. If the waveforms are too far apart a dark band will be apparent where the waveforms merge. If they are too close together a bright band will be apparent. When the adjustment is satisfactorily completed, the coupling selector switch is set to GND for both channels, the vertical distance between the two horizontal lines (cm) divided by two and multiplied by the vertical deflection factor (volts/cm) is the amplitude (volts) of the noise or noisy signal.

4.1.1 C-Band

The C-Band radar and plan position indicators are required to operate according to a predetermined radar operations schedule. The following systems may be operated at the discretion of project management.

1. S-Band Radar
2. X-Band Radar

Regardless of which systems are in operation they must be monitored periodically to ensure they are in proper working order. An operational checklist is provided to record performance checks. Any deviation from the norm should be corrected and noted in the radar log.

4.1.1.1 Antenna checks

The antenna elevation sequence (9 or 21 degrees) should be checked and entered on the checklist. All measurements and checks are recorded on the checklist and entered in the radar log.

4.1.1.2 Transmitter checks

The following parameters should be measured one hour after the transmitter is first turned on then every 2 hours thereafter:

1. Output average power,
2. Pulse width,
3. Output frequency,
4. Spectrum 3 dB bandwidth.

4.1.1.3 Receiver

The C-Band receiver is calibrated by injecting a known signal into the receiver and measuring the output voltages of the logarithmic amplifier, integrator, and threshold levels. The last part of the calibration is the calibration of the computer drivers. The instruments are connected as shown in figure 4.1. The monitor panel is shown in figure 4.2.

4.1.1.3.1 Major calibration

Follow these steps for a manual calibration.

Note: These procedures are to be used only when the automated procedure is inoperative.

1. Set the signal generator to 5635 MHz and the output RF power off.
2. Set the C-Band transmitter to local radiate off and filament switch off. Remove the 12 inch section of wave guide from the waveguide run at the top right hand corner of the transmitter cabinet. Mount the waveguide transition on the Tx/Rx waveguide and connect the signal cable from the signal generator.
3. Set the AFC switch located inside the transmitter cabinet to manual (MFC).
4. Pulse modulate the signal generator with a pulse of appropriate delay and width.
5. Set the signal generator output -20 dBm and adjust the RF frequency to maximize the log amp output pulse. Set the RF frequency to the mid point between the upper and lower frequencies at which the logarithmic amplifier pulse amplitude decreases by an equal amount.
6. Decrease the power on the signal generator until the pulse observed at the logarithmic amplifier monitoring point (monitor panel) can no longer be seen. The signal generator RF power setting plus the signal cable loss is the C-Band logarithmic amplifier MDS. Record this value on the calibration sheet. This should be approximately -105 dBm. Measure the noise voltage as described and enter on the calibration sheet.
7. Set the generator to inject -95 dBm, record the pulse amplitude. Increase the RF power setting in 5 dB steps recording the pulse amplitude for each step until -20 dBm is reached.
8. Repeat steps 4, 6, and 7 for the integrator output (INTC-THR). Plot voltages versus input power on graph paper for the logarithmic amplifier and integrator.
9. Connect an oscilloscope to the threshold amplifier output on the monitor panel (THR-C). Record the power levels at which the grey shades, when viewed with the oscilloscope, are of equal intensity between levels. These levels should be -95 dBm, -82.5 dBm, -70 dBm, -60 dBm, and -50 dBm $\pm$ 0.5 dBm.
10. Do the C-Band computer calibration.
11. Set the AFC switch to the AUTO position and replace the 12 inch section of waveguide.

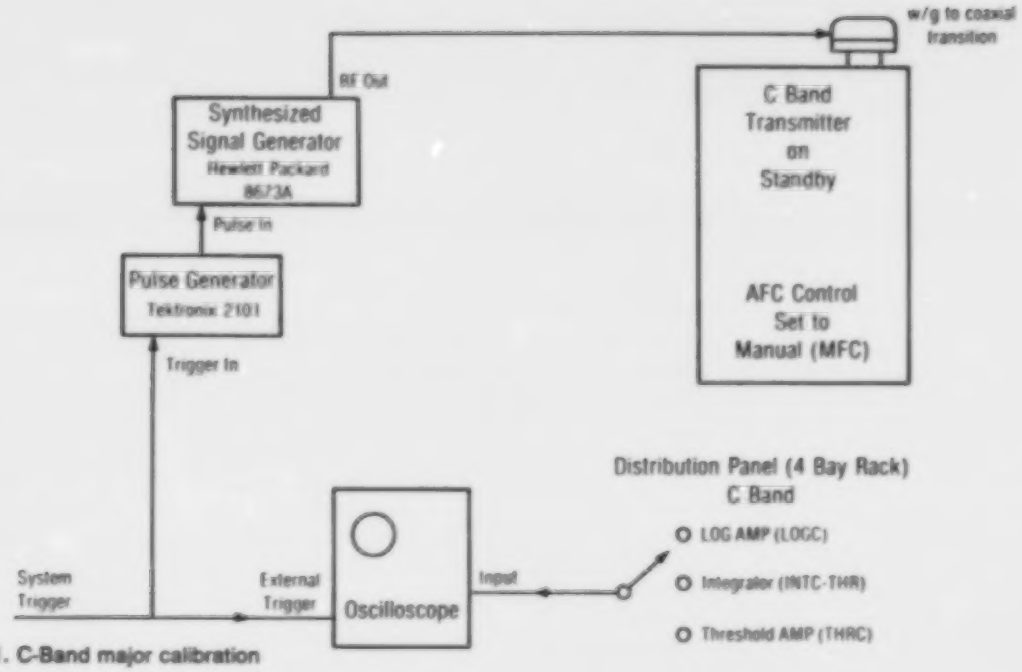


Figure 4.1. C-Band major calibration

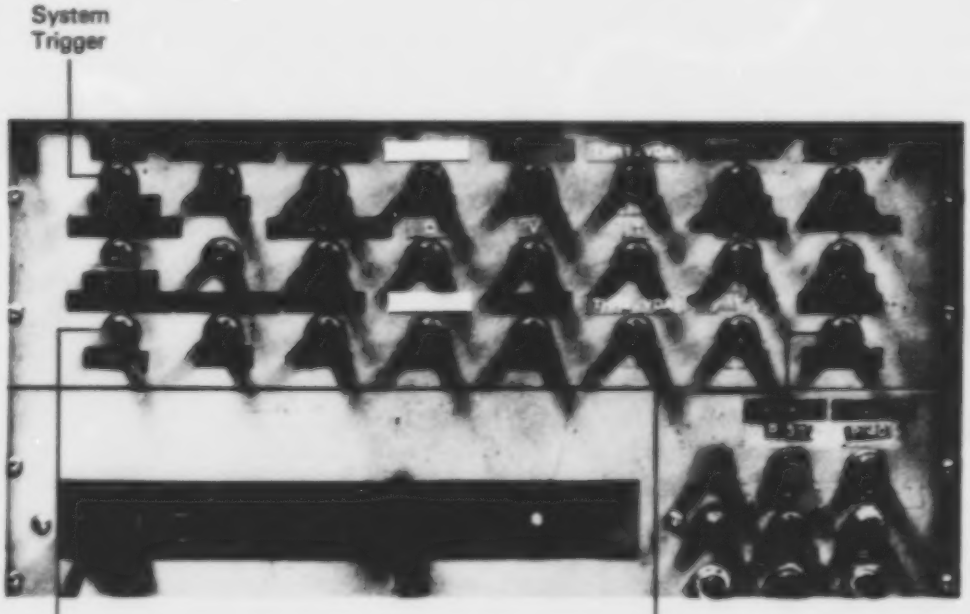


Figure 4.2. Signal monitor panel

Figure 4.2

Suffix 1	=	S-Band Port 1
Suffix 2	=	S-Band Port 2
Suffix C	=	C-Band
THR	=	Threshold
Log VDA	=	Lograthmic Amplifier Video Distribution Amplifier
INT	=	Integrator
DVR	=	Driver
Suffix 3	=	S-Band Port 3
Suffix 4	=	S-Band Port 4

4.1.1.3.2 Computer calibration

Introduction

The C-Band Radar/Computer interfaces located in both the 11/ 34 and 11/44 computers require periodic correlation to the absolute power levels received by the C-Band radar receiver.

Microwave signals simulating simple radar signals are injected into the C-Band receiver. These signals of specific waveshape, frequency, and power are compared to acquired radar data words from the Radar/Computer interface.

Each completed computer calibration creates a data file containing the correlation of radar data words to specific receiver input powers. A data base is maintained which contains computer calibration files. This data base is referenced whenever radar data, either real-time or archived, is used.

Procedure

Both the 11/34 and 11/44 computers support a program called "CALIBC". Whether CALIBC will be fully automatic or interactive is unknown at the time of this writing.

Interactive computer calibration:

CALIBC is a program which performs the C-Band computer calibration. CALIBC interacts with an operator who makes adjustments to test equipment in response to program prompts.

To begin a C-Band computer calibration, an operator sets up test equipment to inject a calibration pulse into the C-Band radar receiver. The operator adjusts the pulse to be delayed from the trigger by 450 microseconds, to have a width of 100 microseconds and to have a power level of -40 dBm.

The operator then runs the program "CALIBC" using a graphics terminal. The program starts by drawing a pulse on the terminal screen which represents the signal as seen by the Radar/Computer interface.

The operator then fine-tunes the pulse position by adjusting the pulse shoulders midway up the pulse on both the rising and falling edges. When the pulse shoulders are tuned satisfactorily, the operator notifies the program that the pulse can be found by typing the command "F". Vertical cursors are then drawn on the terminal screen which frame the pulse position. If the cursors frame one or both the pulse shoulders, the shoulder heights must be readjusted and the pulse found again.

When the pulse is framed properly the operator initiates the power calibration by typing the command "W".

The calibration program then prompts the operator to set the calibration signal to specific power levels. When the power levels are set the operator types a carriage return and the program draws another pulse. The program prompts the operator to check if the pulse is OK. This process repeats for each of the power levels until the program announces "Calibration Complete" and gives the file name for the calibration.

Several one letter commands are available for use by the operator during the calibration.

COMMAND	RESPONSE
A	VALUE OF RELATIVE PULSE HEIGHT IS RETURNED
B	CALIBRATION BACKS UP ONE POWER STEP
D	CALIBRATION TERMINATES AND A FILE IS MADE
E	TERMINAL SCREEN IS ERASED
F	PULSE IS FOUND
Q	CALIBRATION TERMINATES AND NO FILE IS MADE
W	POWER CALIBRATION BEGINS

4.1.2 S-Band

4.1.2.1 Antenna

4.1.2.1.1 Azimuth checks

There are no direct checks. One should however verify, when the antenna is rotating, that it is doing so smoothly and without undue vibration.

4.1.2.1.2 Elevation checks

The antenna elevation sequence (8 or 20 degrees) should be checked and the setting entered on the checklist. All measurements and checks are recorded on the checklist and entered in the radar log.

4.1.2.1.3 Polarization checks

During normal system operation, the polarization dial should be set at a reading of 59403 unless instructed otherwise by the supervisor. Similarly the phase dial should be set at 0.

4.1.2.2 Transmitter checks

The following parameters should be measured one hour after the transmitter is first turned on then every 2 hours thereafter:

1. Output average power,
2. Pulse width,
3. Output frequency,
4. Spectrum 3 dB bandwidth.

4.1.2.3 Receiver

4.1.2.3.1 Major calibration

Follow these steps for a manual calibration.

Note: These procedures are to be used only when the automated procedure is inoperative.

For the S-Band calibration, a known signal is injected into the lower waveguide of the antenna and towards the pedestal. With the antenna polarization control set to linear, the signal is split equally into both receiver ports. The output voltages of the logarithmic amplifiers, range integrators, and threshold levels are measured. The minimum detectable signals (MDS) are also recorded. The CDR threshold levels are then checked by inserting different values of attenuation into port 1. Finally the outputs to the computer are calibrated. Refer to figures 4.3 and 4.4.

1. Set the signal generator output frequency to 2880 MHz and the RF out power off.
2. Set the polarization control to LINEAR (dial reading 58525) and phase chassis SOURCE CONTROL to LOG AMP. Check to make sure the monitor POWER is OFF. Using the slow speed control rotate the S-Band antenna to 210 degrees azimuth and 0 degrees elevation. Put up the DO NOT ROTATE — WORK IN PROGRESS warning sign on the monitor control rack. All transmitters MUST BE OFF before ascending the radar tower. Leave the slow speed clutch and drive engaged to prevent the antenna from moving.

Caution: The slow speed clutch will not hold the antenna during strong winds. Appropriate action must be taken to ensure that damage to waveguides and antenna structures does not occur if calibrations are undertaken during strong winds.

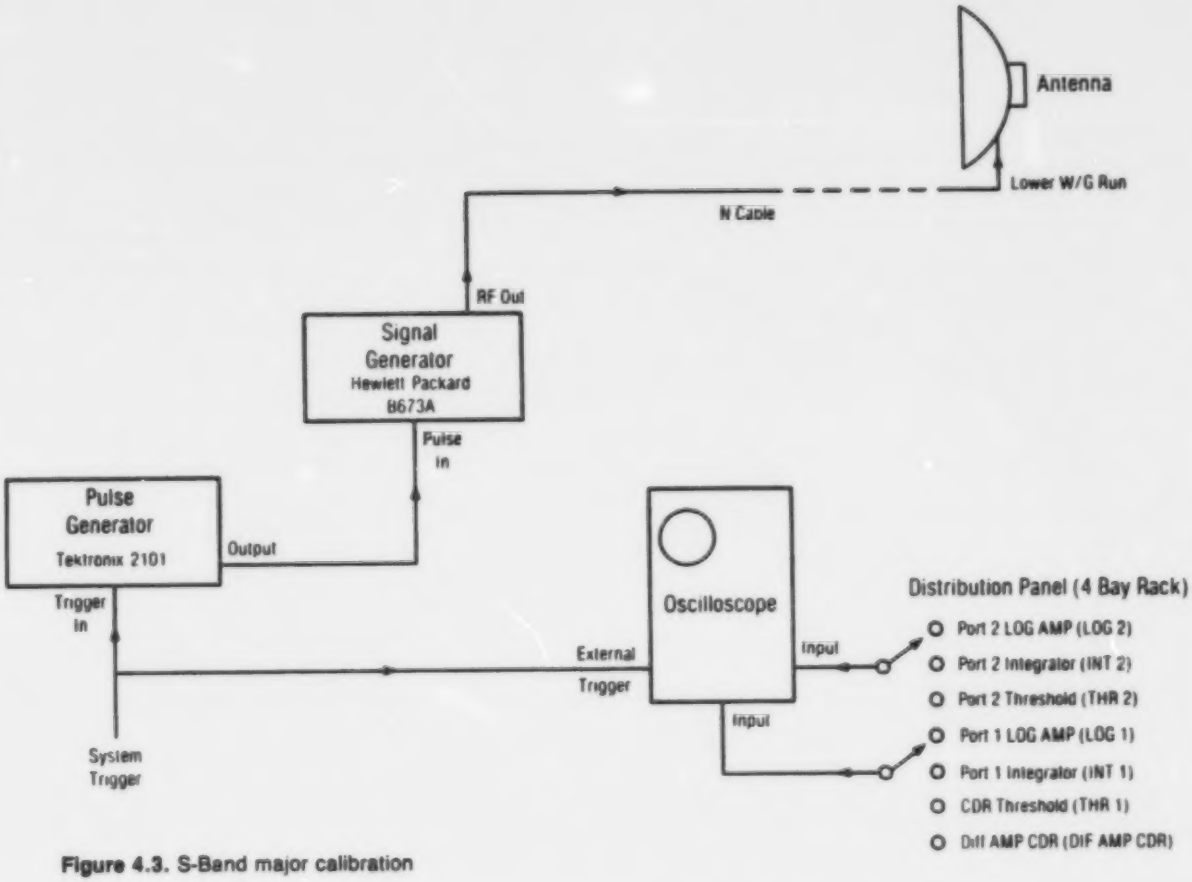


Figure 4.3. S-Band major calibration

3. Disconnect the waveguide elbow at the lower bend of the waveguide on the antenna. Bolt on the type N to waveguide adapter, connect the calibration cable to the adapter. The signal is to be injected towards the pedestal, through the waveguide running behind the antenna dish.
4. Connect an oscilloscope to the logarithmic amplifier outputs 1 and 2 on the monitor panel and observe the logarithmic amplifier signals.
5. Pulse modulate the signal generator with a pulse of appropriate delay and width.
6. Set the signal generator RF power to ON (-20 dBm) and adjust the RF frequency to maximize the logarithmic amplifier output pulse. Set the RF frequency to the mid point between the upper and lower frequencies at which the logarithmic amplifier pulse amplitude decreases by an equal amount.
7. The pulsed power injected into each receiver is equal to the generator RF power setting minus the S-Band calibration cable attenuation (SBCA dB) minus the 3 dB power split in the microwave circuitry. [RF power setting — SBCA - 3]
8. Decrease the RF power from the generator until the video pulse can no longer be seen, do one port at a time. The MDS is typically -115 dBm. Record the MDS and noise level on the calibration sheet.

9. Starting from an injected power level of -100 dBm (-82.4 dBm on the generator), increase the generator RF power in 5 dBm steps to -20 dBm, recording the logarithmic amplifier output voltages for each step, do this for both ports. Plot voltages versus input power on graph paper.
10. Repeat steps 5, 7, and 8 for port 1 and 2 range integrator voltages.
11. Connect the oscilloscope to the port 2 threshold amplifier output on the monitor panel. Vary the generator RF power setting to inject from -100 to -50 dBm and record the power levels at which the grey shades, when viewed on an oscilloscope, are of equal intensity between levels. These power levels should be -100 dBm,-85 dBm, -70 dBm, -60 dBm, and -50 dBm ± 0.5 dBm.
12. Set the signal generator to inject a power level of -40 dBm.
13. Connect the oscilloscope to the differential amplifier terminal on the monitor panel. The differential amplifier output should be approximately 0 volts.
14. Using the port 1 attenuators in the Logarithmic Amplifier Chassis, refer to figure 4.3, dial in attenuation until the port 1 range integrator voltage, viewed on an oscilloscope, equals the output voltage obtained when -45 dBm was injected as measured in step 8. Record the attenuation dialed in and the differential amplifier voltage beside -5 dB CDR on the calibration sheet.
15. Continue in 5 dB steps until -50 dB CDR is reached.
16. Connect the oscilloscope to the CDR threshold terminal on the monitor panel. Increase the port 1 attenuation and record the values at which the CDR grey shades, when viewed with an oscilloscope, are of equal intensity between levels. These settings should correspond to the attenuator values for CDR levels of -5 dB, -10 dB, -15 dB, -20 dB, -25 dB ± 0.5 dB as measured in step 13.
17. A gating circuit is used to turn off the CDR differential amplifier output when the power level in port 1 is below -90 dBm. Monitor the differential amplifier output on the oscilloscope. Increase the attenuation in port 1 until the differential amplifier output switches off. Record the attenuation dialed in on the calibration sheet. This setting should correspond to the attenuation at -50 dB CDR as measured in step 10.
18. Set all attenuators to zero.
19. Run the S-Band computer calibration.
20. Replace the S-Band waveguide elbow, set the polarization control to LHC (59403), remove the warning sign and disengage the antenna slow speed drive and clutch.

4.1.2.3.2 Computer calibration

Introduction

The S-Band Radar/Computer interfaces located in both the 11/34 and the 11/44 computers require periodic correlation to the absolute power levels received and the phase differences discriminated by the S-Band radar receivers. The 11/34 computer interface has two power channels and two phase channels to calibrate. The 11/44 computer interface has one power channel (port 2 only) to calibrate.

Microwave signals simulating simple radar signals are injected into the S-Band receivers. These signals of specific waveshape, frequency, power and phase difference are compared to acquired radar data words from the Radar/ Computer interface.

Each completed computer calibration creates a data file containing the correlation of radar data words to specific receiver input powers or phase differences. A data base is maintained which contains computer calibration files. This data base is referenced whenever radar data, either real-time or archived, is used.

Procedure

Both the 11/34 and 11/44 computers support a program called "CALIBS". Whether CALIBS will be fully automatic or interactive is unknown at the time of this writing.

Interactive computer calibration:
CALIBS, when run on the 11/34 computer is a program which performs the S-Band computer calibration for both received power (ports 1,2) and phase difference (ports 3,4). CALIBS, when run on the 11/44 computer performs the S-Band computer calibration for received power (port 2 only). CALIBS interacts with an operator who makes adjustments to test equipment in response to program prompts.

Power calibration:
To begin a S-Band power computer calibration an operator sets up test equipment to inject a calibration pulse into the S-Band radar receivers. The operator adjusts the pulse to be delayed from the trigger by 450 microseconds, have a width of 100 microseconds and have a power level of -40 dBm.

The operator then runs the program "CALIBS" using a graphics terminal. The program starts by drawing pulses on the terminal screen which represents the signals as seen by the Radar/Computer interface. The pulses will be redrawn each time the operator enters a carriage return.

The operator then fine-tunes the pulse position by adjusting the pulse shoulders midway up the pulse on both the rising and falling edges. When the pulse shoulders are tuned satisfactorily, the operator notifies the program that the pulse can be found by typing the command "F". Vertical cursors are then drawn on the terminal screen which frame the pulse position. If the cursors frame one or both the pulse shoulders, the shoulder heights must be readjusted and the pulse found again.

When the pulse is framed properly the operator initiates the power calibration by typing the command "W".

The calibration program then prompts the operator to set the calibration signal to specific power levels. When the power levels are set the operator types a carriage return and the program draws another pulse. The program prompts the operator to check if the pulse is OK. This process repeats for each of the power levels until the program announces "Calibration Complete" and gives the file names for the calibration.

Phase calibration:
S-Band computer phase calibrations are usually conducted within an S-Band Antenna Calibration when the Monitor is set to a linear polarization.

The operator runs "CALIBS" on a graphics terminal. The program starts by drawing two lines on the terminal screen which represent the signals seen by the power channels of the Radar/Computer interface.

The operator then initiates a phase calibration by typing the command "H". The program erases the screen and instructs the operator to enter the phase shifter setting and type a carriage return when ready.

The operator is expected to go to the S-Band antenna phase and polarization controller and adjust the phase shifter setting in increments of twenty (20) degrees $\pm$ one (1) degree. At each phase shifter increment the operator enters the phase shifter setting and the program puts each new point on a pair of phase channel plots. The process continues until all eighteen (18) points in the full rotation of the phase shifter are plotted. When this is done the operator terminates the phase calibration by typing the command "D". The program then announces "Calibration Complete" and gives the file names for the calibration.

Several one letter commands are available for use by the operator during either the power or the phase calibrations.

COMMAND	RESPONSE
A	VALUE OF RELATIVE PULSE HEIGHT IS RETURNED
B	CALIBRATION BACKS UP ONE POWER STEP
D	CALIBRATION TERMINATES AND A FILE IS MADE
E	TERMINAL SCREEN IS ERASED
F	PULSE IS FOUND
H	PHASE CALIBRATION BEGINS
Q	CALIBRATION TERMINATES AND NO FILE IS MADE
W	POWER CALIBRATION BEGINS

4.1.2.3.3 Antenna calibration

To perform the S-Band antenna calibration, the antenna is pointed at the monitor unit. The monitor's antenna can be set to transmit LHC, RHC, or linear polarized signals. The S-Band polarization control is used to direct the monitor signal to only one channel of the S-Band receiver. With the monitor polarization set to RHC, the signal leakage into the second S-Band receiver channel is measured. The difference between the received signal powers is known as the isolation. When the monitor is set to transmit linearly polarized signals and the S-Band polarization control is set to LHC, equal signals will be received in both channels, allowing signal to noise ratio measurements to be made. Because of the polarization control sequence on the monitor unit, the isolation checks are done in two parts. Refer to figures 4.3, 4.4, and 4.5.

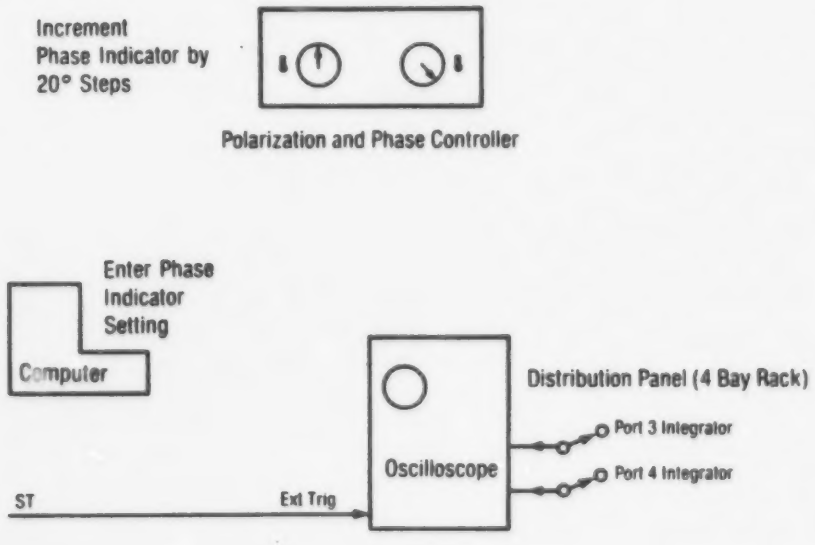


Figure 4.4. S-Band phase discriminator calibration

1. Set the monitor unit POLARIZATION to LHC and turn the monitor POWER to ON. Both monitor unit antenna switches should be in the off position always. Set the phase chassis SOURCE CONTROL switch to TEST RECEIVER. Using the test receiver "port selection switch" select Port 1 as input.
2. Using the S-Band antenna slow speed drive point the antenna at the monitor, azimuth 53.2 degrees, elevation 2.19 degrees.
3. Set the polarization control to LHC (59403) and the phase control to 0 degrees. This will direct the received signal to port 1. *Note:* When setting the polarization or phase control always approach the desired reading from the clockwise direction to eliminate backlash errors.
4. Using the manual elevation control and the antenna slow speed drive maximize the power reading on the test receiver (port 1 as input). Set the port selection switch to port 2 and adjust the test receiver attenuation control to obtain a reading of 100 on the meter. Record the attenuation setting. Select Port 1 with the port selection switch and readjust the test receiver attenuator to obtain a meter reading of 100. Record the attenuation setting. The difference between the two values is the isolation for LHC polarization and is recorded under isolation. This value should be greater than 35 dB.
5. To check the Signal to Noise ratio change the monitor unit POLARIZATION to LINEAR, PORT SELECTION switch to Port 1 and turn the monitor power OFF. Adjust the test receiver ATTENUATION CONTROL to 0 dB or set the meter's pointer to a reference mark. Record these values under dB inserted (noise only) and number of divisions.
6. Turn the monitor power ON and adjust the ATTENUATION CONTROL to place the meter indication to the same reference marker set in the noise level (previous step). Record the attenuation value under dB inserted (signal level). The S/N Ratio is the dB inserted (with signal) minus the dB inserted (noise only).
7. Repeat steps 4 and 5 for Port 2 by changing PORT SELECTION to Port 2.
8. Set the phase chassis SOURCE CONTROL to LOG AMP. Set up the oscilloscope to monitor the phase integrator outputs as shown in figure 4.5 and run the computer phase calibration program. The phase indicator on the polarization and phase control is already at 0 degrees. Record the phase integrator output voltage (ports 3 and 4) on the calibration sheet and enter the phase angle into the terminal.
9. Increment the phase indicator by 20 degrees. Record the voltages and enter the phase angle. Continue until 360 degrees (0 degrees) is reached. A graph of the calibration should be drawn on the terminal. Using a hard copy terminal, produce a copy of the calibration result, the result should be two sine waves out of phase with each other by a consistent amount. These results should be the same from calibration to calibration.
10. Reset the Phase Discriminator SOURCE CONTROL to TEST RECEIVER. Set the monitor to RHC. Set the S-Band antenna polarization to RHC. The signal is now directed into port 2. Measure the isolation for RHC polarization.
11. Set the Phase Discriminator SOURCE CONTROL to LOG AMP, Monitor polarization to LHC, after the Monitor Remote Control current meter goes back to zero, Monitor POWER to OFF, and S-Band antenna polarization to LHC. The antenna and phase calibration is now complete.

4.1.3 X-Band

The parameters measured on the X-Band are the same as those of the S-Band and C-Band. However, the receiving frequency must be monitored closely. If spurious aircraft are observed, recheck the TTL noise threshold.

4.1.3.1 Antenna checks

The X-Band has no elevation drive hence no elevation sequence to check.

4.1.3.2 Transmitter checks

The following parameters should be measured one hour after the transmitter is first turned on then every 2 hours thereafter:

1. Output average power,
2. Pulse width,
3. Output frequency,
4. Spectrum 3 dB bandwidth.

4.1.3.3 Receiver checks

The sensitivity and receiving frequency of the X-Band radar must be checked closely. The tests listed below should be performed once every 24 hours.

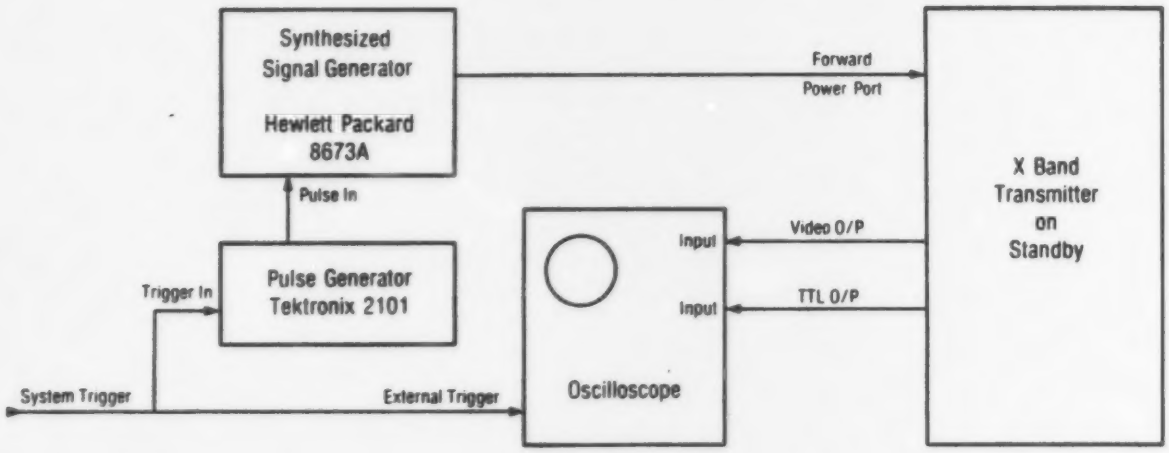


Figure 4.5. X-Band receiver frequency check

Follow these steps for a manual calibration:

Note: These procedures are to be used only when the automated procedure is inoperative.
Note: This series of measurements is done with a pulse width of 10 microseconds delayed 40 microseconds from the radar trigger.

1. Ensure that the transmitter is in the "radiate off" position and that the filament switch is off before connecting the signal generator to the FORWARD POWER port.
2. Set the signal generator frequency to 9.410 GHz.
3. Vary the frequency of the generator until a video pulse is obtained on the oscilloscope connected to the video output on the front of the transmitter cabinet. Maximize the pulse voltage by fine tuning the signal generator.

4. Record the signal generator frequency on the check list. This is the receive frequency of the receiver and should be 9410 MHz. Record the ten turn potentiometer dial reading of the LO FREQUENCY CONTROL located on the front of the transmitter cabinet.
5. If the receive frequency is not 9410 MHz, adjust the signal generator frequency to 9410 MHz and fine tune the LO FREQUENCY CONTROL to maximize the video pulse. Record the LO FREQUENCY'S 10 turn potentiometer dial reading on the check sheet.

X-Band receiver sensitivity check

Follow these steps for a manual calibration:

Note: These procedures are to be used only when the automated procedure is inoperative.

1. Turn transmitter off by placing the filament switch in the OFF position.
2. Adjust the signal generator to 9410 MHz. Connect a 50 ohm coaxial cable with type N connectors to the output of the signal generator. Attach a power meter to the other end of the cable using a type N female to female adaptor. Set the RF power setting on the generator to obtain -20 dBm at the end of the cable. (-20 dBm is used as a power reference and to ensure the receiver front end is not driven into saturation). Remove the power meter and connect the cable to the forward power terminal on the X-Band transmitter cabinet.
3. Modulate the signal generator with a 0.5 microsecond pulse delayed 40 microseconds from the system trigger.
4. Observe the video pulse on an oscilloscope connected to the video output terminal on the front of the X-Band transmitter cabinet.
5. Increase the attenuation until the 0.5 microsecond pulse just disappears in to noise. The minimum detectable signal (MDS) will be the sum of:
   a) The difference between the present RF power setting and the RF power setting of step 1 above
   b) -20 dBm
   c) the insertion loss of the forward power coupler
   The insertion loss of the forward power coupler is labeled on the front of the cabinet under the forward power connector.Record the 0.5 microsecond pulse MDS in the check list.
6. Adjust the pulse generator to obtain a 10 microsecond pulse. Repeat steps 3 and 4 to measure and to record the 10 microsecond pulse MDS.
7. The 0.5 microsecond pulse MDS should be in the order of -105 dBm and the 10 microsecond pulse MDS in the order of -110 dBm. Inform your supervisor if these minimum values are not obtained.
8. Measure and record the average and peak noise voltage. Refer to notes on measuring noise and noisy signals using a multichannel oscilloscope.

TTL noise threshold check

1. Connect an oscilloscope to the TTL (transistor transistor logic) terminal on the front of the X-Band transmitter cabinet. This is a signal derived from the logarithmic amplifier signal to eliminate noise and detect pulses. Signals within 100 microseconds of the system trigger are blanked out to reduce the "ring-around effect". A ten turn potentiometer, TTL THRESHOLD, on the front of the X-Band transmitter cabinet controls a noise threshold, signals below the set threshold are blanked out.
2. Place the STC switch inside of the transmitter cabinet to the OFF position. Set the calibration pulse to 0.5 microseconds. Adjust the pulse generator delay to bring the pulse out of the blanking range, a 400 microseconds delay is adequate. Adjust the oscilloscope as necessary to obtain a stable display, timebase = 100 microseconds/division.

3. Turn the noise threshold control CCW to increase the sensitivity until noise spikes are observed on the oscilloscope. Then rotate the noise threshold control clockwise until the noise spikes completely disappear. Record the threshold dial reading on the check sheet.
4. Decrease the generator RF output level until the TTL out pulse flickers on no more than once per second. This MDS is to be recorded on the check sheet under TTL MDS OFF.
5. Increase the signal generator RF output level until the TTL out pulse appears, flickering no more than once per second. This MDS is to be recorded on the check sheet under TTL MDS ON.
6. TTL MDS OFF should be in the order of -85 dBm and TTL MDS ON should be in the order of -80 dBm. If these minimum values are not obtained inform your supervisor.
7. Disconnect the cables from the forward power port and TTL output terminals, place the STC switch to the on position. The X-Band is now ready for normal operation.

4.1.3.4 Aircraft tracking unit checks

The aircraft simulator is used to check the Aircraft Tracking Unit's operations. It is possible to simulate a maximum of 4 aircraft codes at any one time. To operate follow these instructions (Refer to figure 4.6).

1. Rotate the X-Band antenna and the weather radar antenna as selected by the reference radar control switch.
2. Set the MASTER CONTROL switch to the SIMULATED position, a red LED on the right of the panel will start to flash.
3. Select the desired codes using the Code Selector switches. Enable these codes by switching the ENABLE control switches to the up position.
4. The RANGE CONTROL potentiometers set the range of the aircraft from the center of the PPI. They should be set to the midrange position.
5. The azimuth bearing of the aircraft position is the sum of the azimuth degrees switched on (up position) by the Azimuth Control switches. All combinations of azimuth switches should be checked.
6. Turn on the PPI. The simulated aircraft will be displayed as a series of dots and dashes.
7. Select various azimuth bearings and ranges. The displayed positions should correspond to the switch settings on the simulator. If they do not, check that the Reference radar select switch is in the proper position. If problems persist, inform your supervisor.
8. Check all 8 transponder codes at different azimuths and ranges to ensure the aircraft tracking unit is working correctly.
9. The row of LEDs monitor the binary azimuth reading of Weather radar AZimuth (WAZ), Other Radar azimuth (OR), AirCraft radar azimuth (AC), or Weather radar ELevation (WEL). The LEDs monitor the bearing or elevation selected by the Monitor Select switch which is located on the top left corner of the aircraft simulator.
10. Return MASTER CONTROL switch to X-BAND position, turn the PPIs off and stop all radar antennas from rotating after test is complete.

4.1.4 Support

4.1.4.1 Computer checks

There are no computer checks, however the tape drive heads should be cleaned daily.

4.1.4.2 Plan position indicator checks

When the radars are operating, the following parameters on the PPIs must be checked and recorded:

1. Gray Shades are between the 70 and 80 mile range rings and are located in either the southwest or southeast quadrant.
2. Range Rings are round. The 60 mile range ring should be accented and on the aircraft control PPIs superimposed on the overlay marker.
3. Aircraft are being displayed and are in the correct positions.
4. Correct position of land marks.
5. Echoes of precipitation are clear and distinct.
6. All lights and dimmer switches are operating correctly.

4.1.4.3 Standby power generator (Cummins) checks

Fuel level must be checked daily.

4.1.4.4 Statistical multiplexer (Gandalf) checks

Normal Indications	
RUN	ON
LINK DCD	ON
LINK UP	ON
AUTO RESTART	OFF
TEST ON	OFF
TEST FAIL	OFF
TRAFFIC LOST	OFF
TxRx	Will flash according to data activity on the synchronous link, when the link is up.
LINK ERROR	Will flash occasionally, indicating retrans mission due to error. Even on a bad link it should not flash more than once or twice per minute.
TRAFFIC HEAVY	Will flash occasionally according to buffer loading.

4.1.4.5 Time checks

Periodically check the operation of the various real time clocks. The System Clock, the Remote Data Tansmission clock, and both 11/34 and 11/44 computer real time clocks must be checked. The clocks should be within 5 seconds of Universal Coordinated Time. If they are, enter the difference between true and indicated times in the radar log. If the clocks are fast or slow by 5 seconds or more, reset them to indicate the correct time and report this resetting in the radar log.

4.1.4.6 Remote data transmission system (EMSC) checks

The aircraft tracking unit test procedure can be used to provide signals for checking the operation of the Remote Data Transmission System. These checks are outlined in the following list.

1. PPI displays should scan smoothly without jerking or jumping positions.
2. Elevation display readings should sequence correctly.
3. Time displays should display time correctly.

When the checks are complete switch off all of the PPIs. Stop the radar antennas. Return the simulator MASTER CONTROL to the X-Band position.

4.2 Measurement and test equipment

Calibration of test equipment is beyond the scope of this manual.

Appendices

Appendix A. Detailed description and operation

A-I. Electronic systems

A-I-i. C-Band

A-I-ii. S-Band

A-I-iii. X-Band

A-I-iii-a. Transponders

Transponder maintenance

The object of the transponder maintenance schedule is to ensure the transponders have specified sensitivity, and are transmitting and receiving on the correct frequencies. Enter all test results on the maintenance form provided.

A test bench has been set up to facilitate testing of the transponders. Connect the equipment as shown in figure A-1. Do not hesitate to contact your supervisor if any problems or questions arise.

Set the power supply to 24 volts. Measure and record the uninterrogated current.

To test the transponder receiver, the signal generator is set to provide a calibrated RF pulse at 9475 MHz (the transmit frequency of the X-Band radar). The RF pulse interrogates the transponder which then responds with a coded pulse at 9410 MHz (the receive frequency of the X-Band radar).

Receive Frequency of Transponder

1. Set the signal generator up to provide a pulsed 2 microsecond RF signal delayed by 400 microseconds from the system trigger at a frequency of 9475 Mhz.

2. Connect the oscilloscope mounted in the four bay rack to the BNC video terminal on the transponder test plate. Trigger the scope externally with system trigger.

3. Set the oscilloscope for delayed sweep mode and observe the video pulse. Vary the frequency of the signal generator to maximize the video pulse. This should occur at 9475 MHz. Inform your supervisor if the frequency is off by more than 2 MHz.

Minimum Detectable Signal (MDS) of Transponders

1. Set the signal generator to 9475 MHz. Connect the crystal detector and variable attenuator to the directional coupler, connect the crystal detector output to the oscilloscope. Observe the response pulses from the detector on the scope, adjust the variable attenuator to obtain a pulse amplitude of 10 mV.

2. Decrease the power of the signal generator until the pulse observed on the scope just begins to flicker.

3. The MDS is the signal generator output power minus the total insertion loss between the signal generator output and the transponder. It has been measured and is labeled on the transponder test set.

   MDS = (signal generator power out) – (total insertion loss)

4. The MDS should be better than –65 dBm. If it is not, the receive frequency may be off and require tuning. Inform your supervisor.

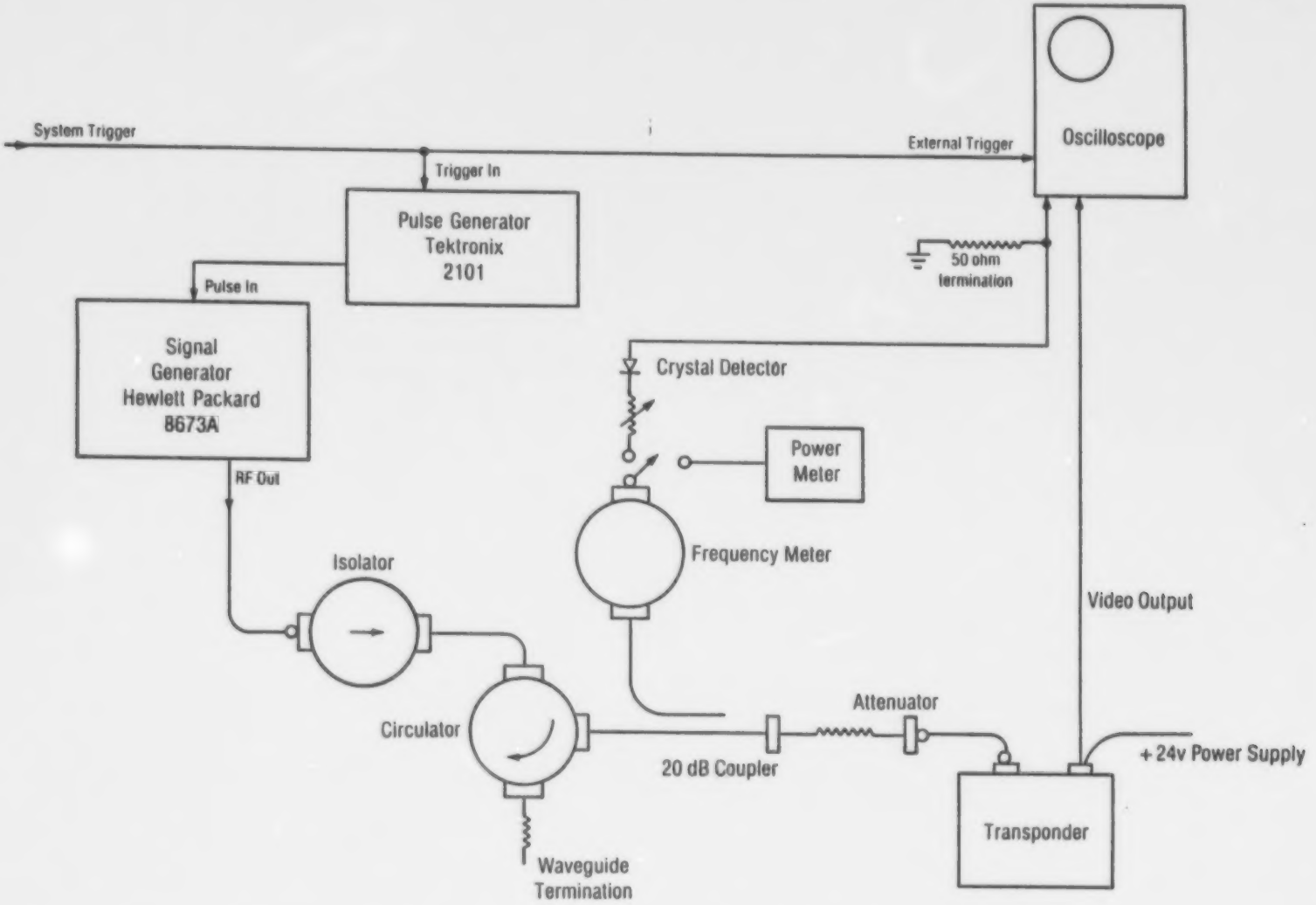


Figure A-1. Transponder test set-up

Output frequency of transponders

1. Adjust the waveguide frequency meter until a dip is observed in the detected crystal pulses on the oscilloscope. The meter should read 9410 MHz. Inform your supervisor if the transmit frequency is out by more than 2 Mhz.

2. Ensure the frequency meter is detuned at least 10 MHz from the operating frequencies when not in use.

Pulse separation of transponders

1. Check the code marked on the transponder.

2. The pulse separation as measured on the oscilloscope should be as indicated in table A-1. If it is not, remove the screw cover marked CODE SEL and verify that the digit displayed on the code select switch corresponds to that marked on the transponder. If it does not, set the switch to the correct code and recheck the pulse separation. If the displayed digit is correct, the transponder has developed a malfuction and requires servicing. Inform your supervisor.

Table A-1. Transponder code and pulse separation

Transponder code	Pulse separation (microseconds)
2	48.8
3	61.0
4	73.2
5	85.4
6	97.6
7	109.8
8	122.0
9	134.2

Output power of transponders

1. Disconnect the crystal detector and variable attenuator, and connect the power meter to the wavemeter.

2. Measure the average power and calculate the peak power from the following formula;

$$\text{peak power} = \frac{\text{average power} \cdot \text{coupling factor}}{\text{pulse width} \cdot 2 \cdot \text{PRF}}$$

For the transponder specified pulse width of 0.3 microseconds, a PRF of 478/sec and a coupling factor of 21.4 dB the peak power will be

peak power (microwatts) = average power (microwatts) • 0.479

or

peak power (dBm) = average power (dBm) + 56.81 dB

3. The peak power should not be less than 300 watts (24.77 dB or 54.77 dBm)

4. Record the interrogated transponder current.

For more detailed information please refer to the equipment manual.

A-I-iv. Support systems

A-I-iv-a. Computers

For detailed information please refer to the equipment manual.

A-I-iv-b. Fibre optic transmission system (Foundation)

FI-6101 PS Power Supply — distributes all necessary power to modules. Front Panel LED's indicate presence of the ± DC voltage available to the mainframe.

FI-6300 T/R Video Link — designed for communication of standard video signals (1 Vpp into 75 ohm).

FI-6300 T Video Transmitter — provides a video to optical interface.

FI-6300R Video Receiver — provides a high performance optical to electrical interface.

Specifications

Input/Output Signal	1.4 Vpp maximum
Input/Output Impedance	75 ohm
Bandwidth	10 Hz to 15 MHz

FI-6400T/R Data link

The FI-6400T/R Data Link is designed for communication of digital data at rates between 0 and 5 Mb/s NRZ (Non-Return to Zero). The circuit converts TTL level input signals to an internal 3 level code which is transmitted by a high radiance LED. At the receiver, the code is converted back to standard TTL levels. This 3 level code places no restrictions on the data format. The link will permit long range, low error rate communication by the use of a high sensitivity, wide dynamic range receiver.

Specifications and performance

Optical Output	8 μW min (15 μW typ)
Optical Input	200 nW Required for 10^{-9} BER
Permitted Link Loss	16 dB Total Loss — no margin
Data Rate	0-5 Mb/s
Optical Rise/Fall Time	20 nsec max (15 nsec typ)
Electrical Rise Time	20 nsec max (15 nsec typ)
Electrical Fall Time	7 nsec max (5 nsec typ)
Jitter	25 nsec typical

FI-6400T Transmitter

This module provides a TTL level-to-optical interface which places no restrictions on the users data. An internal 3 level coder sends a train of pulses with positive or negative excusions about a "mid-level" flux. When the input data is high, a train of positive excursion pulses are generated. These pulses are approximately 150 ns in duration with a 600 KHz repetition rate. When the data changes to a low level this pulse train is terminated even in mid pulse and immediately a negative excursion pulse train is started.

FI-6400R Receiver

This module provides for reception of the optical 3 level code (explained above) and converts it to TTL output levels. The receiver employs a DC restorer and ALC to optimize reception down to a mid-flux level of 200 nW. The receiver indicates if the incoming optical level is large enough to assure a low error rate by the front panel "Carrier" LED.

For more detailed information please refer to the equipment manual.

A-I-iv-c. Standby power generator (Cummins)

The standby power generator is owned and maintained by Alberta Government Services in Red Deer.

A-I-iv-d. Statistical multiplexer (Gandalf)

General Information

The PIN9103 is a Statistical Multiplexer that permits up to 32 asynchronous data channels to be concentrated onto a single high speed synchronous link. This economically replaces the need for multiple links needed to convey the same amount of data between two points.

Data concentration is accomplished by eliminating non-essential data bits (start/stop), then assigning link bandwidth dynamically according to the short term activity of each channel. HDLC (High-Level Data Link Control) protocol is used along with a higher level protocol within the information frame to identify destination address and byte count and to perform internal flow control functions. HDLC error checking and retransmission techniques are used to detect and correct errors occurring on the high speed link.

For complete information on the PIN9103 with software 1674 revision D3 (as installed May 1983), refer to the technical manual.

Abridged Specifications

Multiplexing Technique

Statistical; asynchronous data and interface control signals.
Efficiency: 106%

Asynchronous Channels (Up to 32)

Interface: EIA RS232C and CCITT V.24/V.28
Data Rates: 0 to 9600 bps
Character Formats: 5,6,7 or 8 data bits, any parity, 1, 1 1/2 or 2 stop bits.
Flow Control: CTS, XON/XOFF or Bell warning
Local Echo: Operator enabled
Maximum Aggregate Input Rate: 76,800 bps

High Speed Synchronous Channel

Protocol: HDLC
Error Detection: 16 bit CRC per HDLC
Error Recovery: ARQ (Automatic Request for Retransmission)
Interface: EIA RS232C and CCITT V.24/V.28
Speed: Up to 19.6 Kbps. (Firmware 1674 revision D3)

I/O Module

Each I/O Module carries the following controls, indicators, and test points.

Channel Select

Data activity on any asyncronous channel may be monitored by setting the CHANNEL SELECT thumbwheel switch to the desired channel. The RxDATA and TxDATA indicators flash when SPACE signals occur on the selected channel. Note that the TxDATA indicator confirms the presence of data only, and not that the data is being transmitted (e.g., the channel may be set to inactive status).

Test Points

For troubleshooting purposes, the test points provide convenient access to the PIN9103 operating voltages.

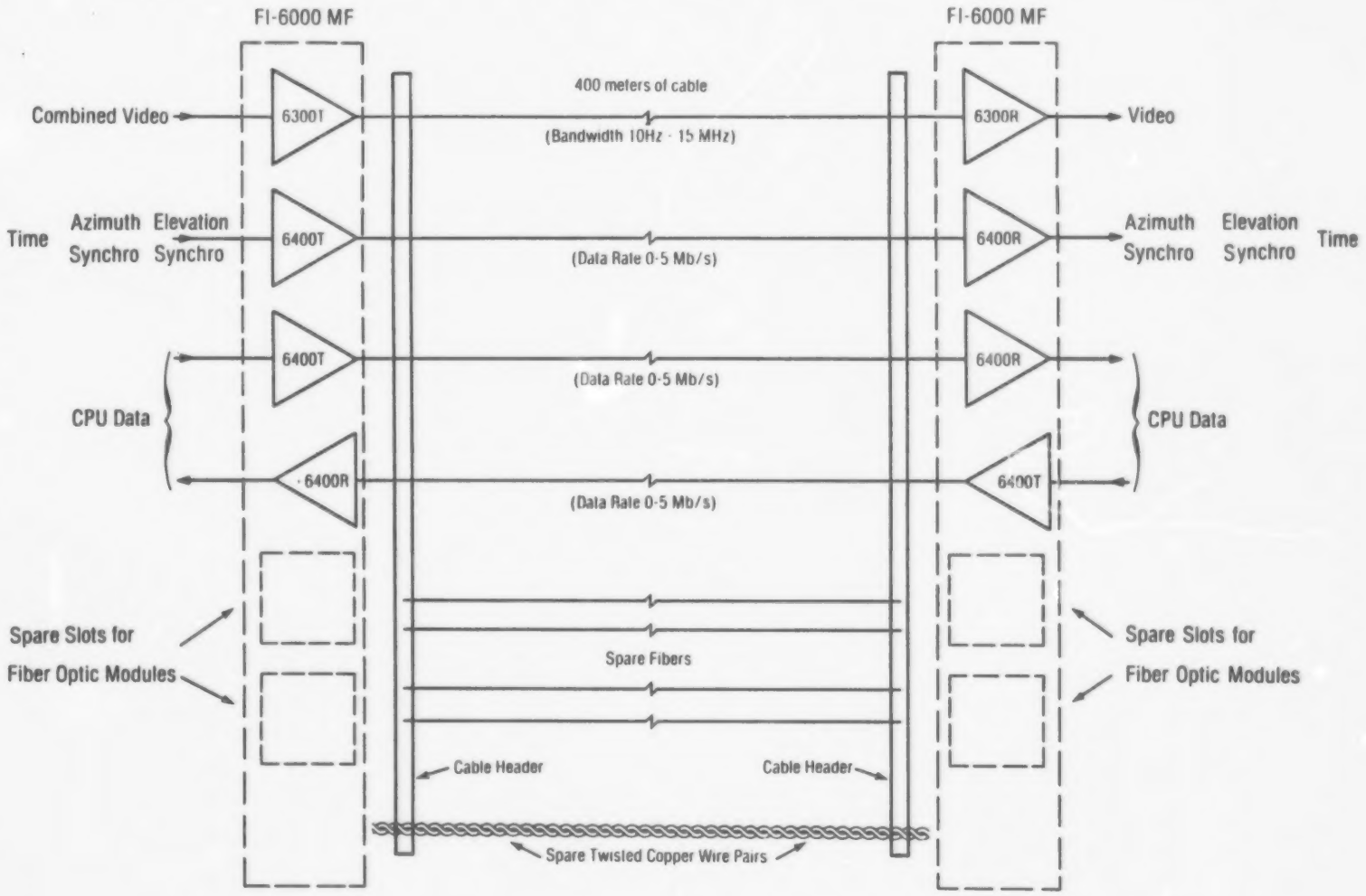


Figure A-2. Fibre optic transmission system block diagram

Battery Test
When power is off, that portion of the memory which holds the configuration information is protected by a rechargeable battery. Battery condition may be checked by momentarily depressing the BATTERY TEST pushbutton and confirming that the indicator lights. Battery capacity is sufficient to retain the configuration data for about 3 months.

Note: Do not hold the BATTERY TEST pushbutton in for more than 10 seconds while the power is off. The LED indicator discharges the battery at a much greater rate than the memory and parameter data could be lost.

CPU Module
The CPU Module carries the following controls, indicators and test points.

Console Group
The CONSOLE switch operates as follows:
In the OFF position, channel 0 operates as one of the asynchronous channels.

The ON position configures the channel 0 interface as the Operator Interface so that it may be used to enter parameter information.

The CH0 REM position also configures channel 0 as the Operator Interface. However, the interface is not active unless the Ring Indicator signal (Interface pin 22) is active.

The CONSOLE ENABLED indicator lights when the switch is in the ON position and in the CH0 REM position if RI is active. The indicator will also light when the Operator Interface is active at the remote end of the link.

Link Indicator Group
DCD
When the DCD indicator is on, the Data Carrier Detect signal from the synchronous modem is active.

ERROR
The ERROR indicator lights for a period of one second when a data error is detected on the synchronous link. Because the protocol provides for retransmission to correct the error, the indicator does not imply errors in user data. Line quality may be roughly determined by the frequency at which the lamp flashes.

RxTx
This indicator reflects both receive and transmit activity on the synchronous link. Even without data traffic, the indicator will flash from time to time as the multiplexer maintain internal communication (or attempt to re-establish communication if the link is down).

LINK UP
When the UP indicator is on, the communications protocol has been successfully established. Provided the units can recover, the link will remain up during short outages and/or severe error bursts. When the protocol "decides" that communication is no longer possible, the indicator will be turned off and traffic may be lost.

Synchronous Channel

Communication between the two units can be at any synchronous speed up to 19,200 bps. The interface to the communications equipment conforms to EIA RS232C and CCITT V.24, pin assignment is shown in the following table.

Pin no.	Description	Abbrev.
1	Chassis Ground	GRD
2	Transmit Data	TxD
3	Receive Data	RxD
4	Request to Send	RTS
5	Clear to Send	CTS
6	Data Set Ready	DSR
7	Signal Ground	GND
8	Data Carrier Detect	DCD
9	+ 12 VDC (Test Voltage)	-
10	– 12 VDC (Test Voltage)	-
15	Serial Clock Transmit	SCT
17	Serial Clock Receive	SCR
20	Data Terminal Ready	DTR
24	2400 Hz Test Signal[1]	-

[1]Present only during self-test

Unlisted pins not used or implemented.

Asynchronous Terminal Channels

The PIN9103 accommodates up to 32 asynchronous terminal channels, each of which can operate independently at speeds from 50 to 9600 bps using any character format having from 5 to 8 bits. The interface to the communications equipment conforms to EIA RS232C and CCITT V.24, pin assignment is shown in the following table.

Pin no.	Description	Abbrev.
1	Chassis Ground	GRD
2	Transmit Data	TxD
3	Receive Data	RxD
4	Request to Send	RTS
5	Clear to Send	CTS
6	Data Set Ready	DSR
7	Signal Ground	GND
8	Data Carrier Detect	DCD
20	Data Terminal Ready	DTR
22	Ring Indicator	RI

Unlisted pins not used or implemented.

For more detailed information please refer to the equipment manual.

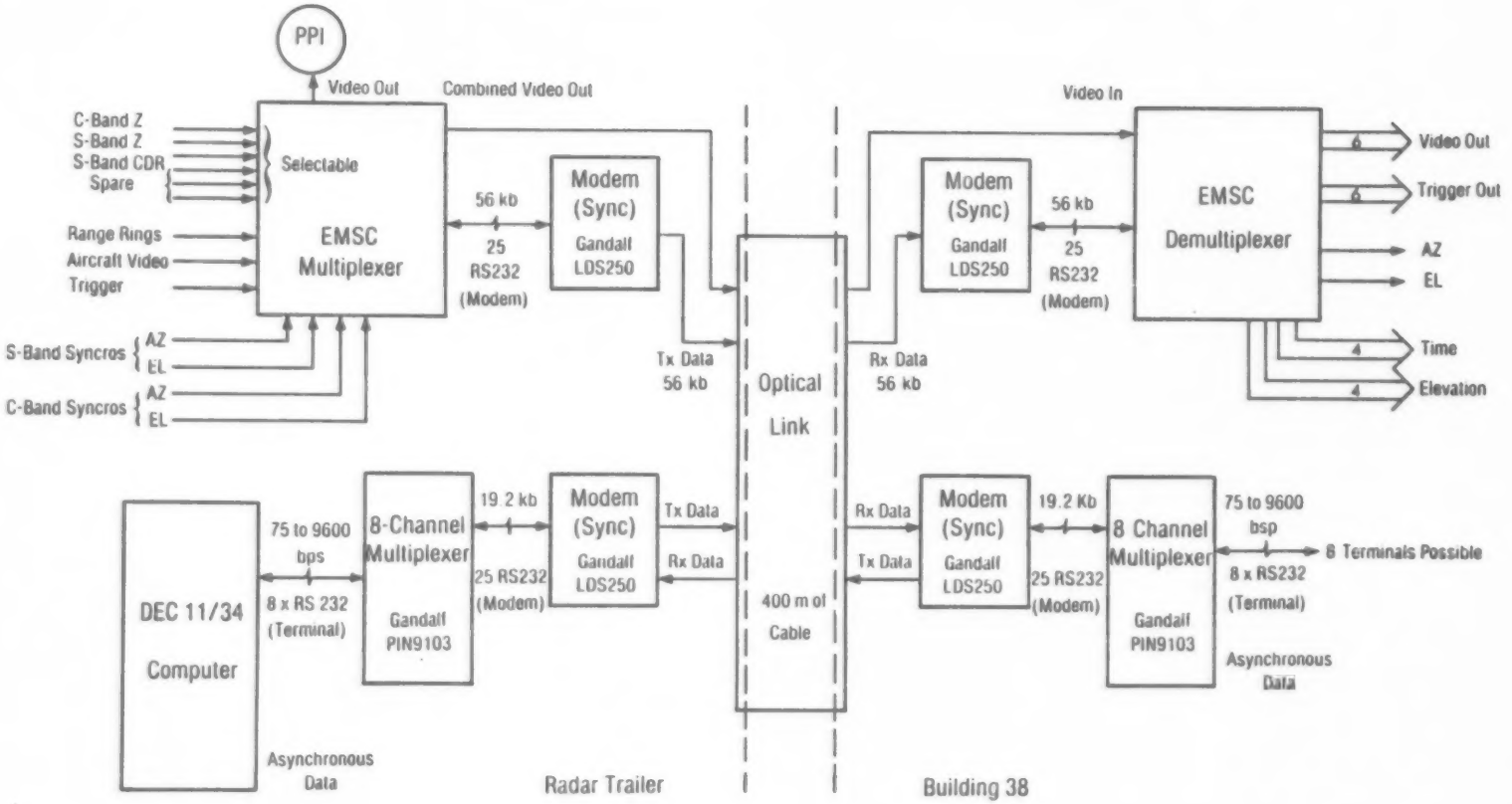


Figure A-3. Remote radar system system block diagram

A-I-iv-e. Remote data transmission system (EMSC)

The remote data transmission system transmit unit combines and formats radar data for transmission to a master control console in building 38 via a fibre optic link. Grey scale video from a selected radar is combined with range rings, aircraft position markers, and trigger pulses into a single analog signal. Azimuth and elevation data from the selected radar are digitally combined with an internally generated real time clock. A corresponding remote data transmission system receive unit in building 38 converts the combined radar signals into composite video, trigger, and synchro signals for driving the PPI displays and digitally drives the elevation and time displays in the master control console. The transmit and receive units comprise a one-way link.

The digital signal is sent via a modem, the fiber optic link, and a modem to the receive unit. The analog signal goes directly to the fiber optic link and then to the receive unit. The digital data is demultiplexed and distributed to various displays on the master control console. The analog signal is restored into composite video and trigger signals which are both buffered by six analog drivers. The buffered signals are distributed to the PPIs in building 38.

The transmit unit is located in the radar trailer and the receive unit is located in the equipment room beside the seeding control room.

For operation see section 3.1.4.7.

For more detailed information please refer to the equipment manual.

A-I-iv-f. Modem — Gandalf LDS250

Modems are used to provide serial asynchronous communications across a data link. Two sets of modems drive and receive data via the fibre optic link. One set of modems connect the Statistical Multiplexer in the radar trailer to the Statistical Multiplexer in building 38 bi-directionally. Another set of modems connect the Remote Data Transmission System transmitter to the Remote Data Transmission System receiver uni-directionally.

For more detailed information please refer to the equipment manual.

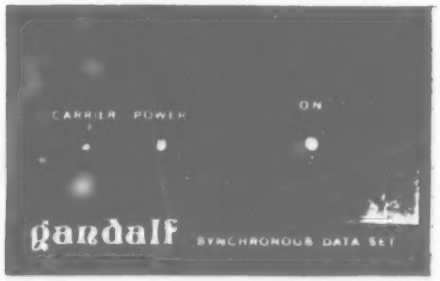


Figure A-4. Gandalf modem model LDS250

A-II. Measurement and test equipment

A-II-i. Basic

A-II-i-a. Multimeter

A-II-i-b. Power meter

A-II-ii. Time domain

A-II-ii-a. Oscilloscope

A-II-II-b. Crystal detector

Crystal detectors are general-purpose components, widely used for CW or pulsed-power detection, levelling of sweepers, and frequency-response testing of other microwave components.

The key specifications for crystal detectors are:

1. Broadband frequency coverage
2. Flat frequency response
3. Low SWR
4. Good Square-law performance.

Broadband operation is important because it eliminates the need for several octave-band detectors to cover a wide frequency range. This is a convenience to the user in that one detector can be used for all detector applications.

Flat frequency response and low SWR are highly desirable because they directly yield more accurate measurements.

When crystal detectors are used in reflectometer and insertion loss setups, the square-law detection characteristic (where the output voltage is proportional to the input RF power) is often depended on for system accuracy. Most microwave diode detectors operate in the square-law mode from the Tangential Signal Sensitivity (TSS) level up to about −20 dBm. The TSS level is determined by the diode characteristics and the bandwidth of the instrument used to display the output of the detector.

By selecting an appropriate loading resistor, the detector more closely follows the square-law characteristic over a wider dynamic range, although the sensitivity is decreased by a factor of four.

For more detailed information please refer to the equipment manual.

A-II-II-c. Standing wave ratio meter

The parameter which characterizes a transmission line is VSWR (Voltage Standing Wave Ratio) — the ratio of the maximum line voltage to the minimum line voltage. A VSWR reading of unity indicates that a generator and it's load are perfectly matched. A disturbance of characteristic impedance in either the generator, the transmission line, or the load causes reflections, which in turn, produce a standing wave ratio (SWR) greater than unity that can be measured and interpeted. For high power sources like a radar transmitter, this mismatch can cause arcing and severe damage to high power microwave tubes like the magnetron.

The VSWR parameter is of considerable importance in practice for the following reasons: At microwave frequencies instruments for the direct absolute measurement of voltage or current are difficult to construct and use. On the other hand, devices to measure voltage or current (or electric or magnetic field) amplitudes are easy to construct. A typical device is a small probe inserted into the region of the electric field around a line (slotted line method). The output of the probe is connected to a crystal rectifier, and produces an output current which is a measure of the relative electric field or voltage at the probe position. By moving the probe along the line, the standing-wave ratio can be measured directly in terms of the maximum and minimum probe currents.

Operation

General Rules of Precaution

For operation of the SWR meter, slotted line and crystal detector probe, the following rules must be observed:

1. Detector must operate in the square law region (output voltage is linearly proportional to the input power). Mathematically, $V_o = \gamma P_{in}$
   where (γ) = open circuit voltage sensitivity (mV/mW)
   V_o = output voltage (mV)
   P_{in} = power in to detector (mW)

   Detectors operate in the square law region for input powers of between – 20 dBm and – 70 dBm. To check the validity of this condition reduce the RF signal level by a known value and see if the SWR meter indication has been reduced by the same amount. If this condition is not satisfied reduce the RF power level to the detector until you reach the square law region of the detector.

2. Crystal diode detectors need careful handling as they are susceptible to damage by capacitive and static discharges. Therefore, equipment and cables should be grounded before connection to the detectors to prevent any discharge from going through the detector. Maximum input power of no greater than 100 mW peak or average, must be applied to the detector.

3. A general rule in slotted line measurements is to use minimum probe penetration that will still pick up adequate signal levels. To find out whether a given probe penetration is too great or not, measure SWR, then change probe penetration and remeasure SWR. If the second reading is different, the probe is penetrating too far and loading the transmission line significantly.

4. The input switch of the SWR meter should be set at XTAL IMPED/HIGH for a maximum input signal. For applications where noise causes problems XTAL IMPED/LOW can be used to reduce the noise level.

5. Always start with the RANGE switch in the least sensitive position (0 dB) and the EXPAND switch to the normal position to protect the meter. Reduce to a more sensitive range to obtain a meter reading if necessary.

6. An isolator should be connected before the slotted line input to minimize source SWR error.

7. To reduce ground current, DC drift, and noise problems, the signal source is modulated by a 1 kHz square wave signal.

Hewlett Packard SWR meter model 415E

To measure the SWR of a device, follow these steps (refer to figure A-5):

1. Set the test equipment up as in figure A-5. Connect the signal generator (modulated by a 1 kHz square wave), to a slotted line through an isolator. This prevents mismatches between the signal generator and the slotted line from influencing the device under test. A coaxial to waveguide adaptor will be needed to connect the isolator to the signal generator. Connect the device under test to the other side of the slotted line. Mount crystal detector probe (PRD model 250A, AR0079) to the slotted line carriage.

2. Set probe to minimum depth using the Probe Depth control.

3. Set SWR meter input to the XTAL IMPED/HIGH position.

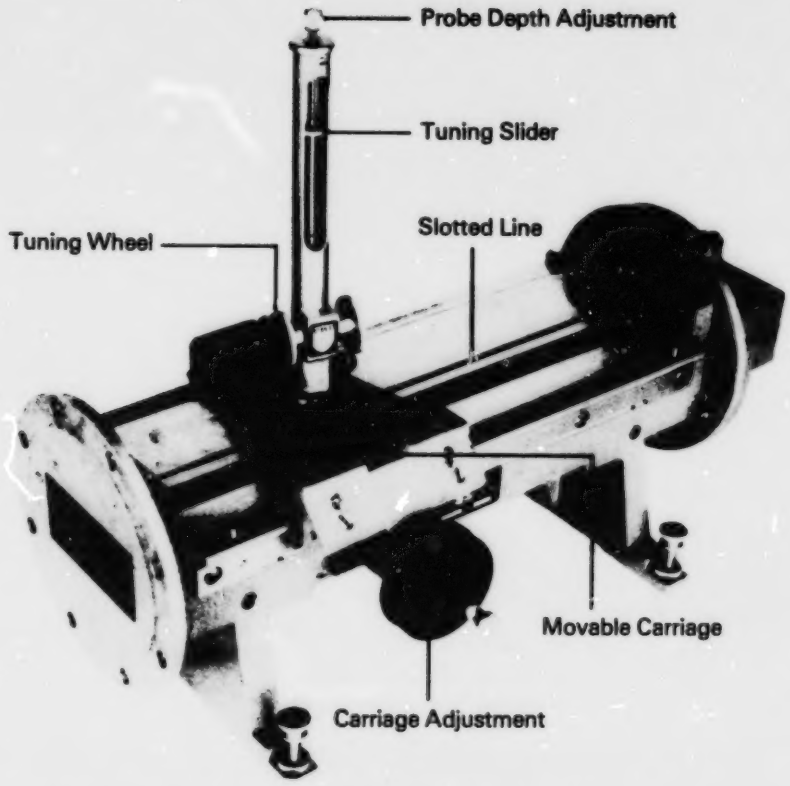


Figure A-5 PRD crystal detector probe model 250A and S-Band slotted line

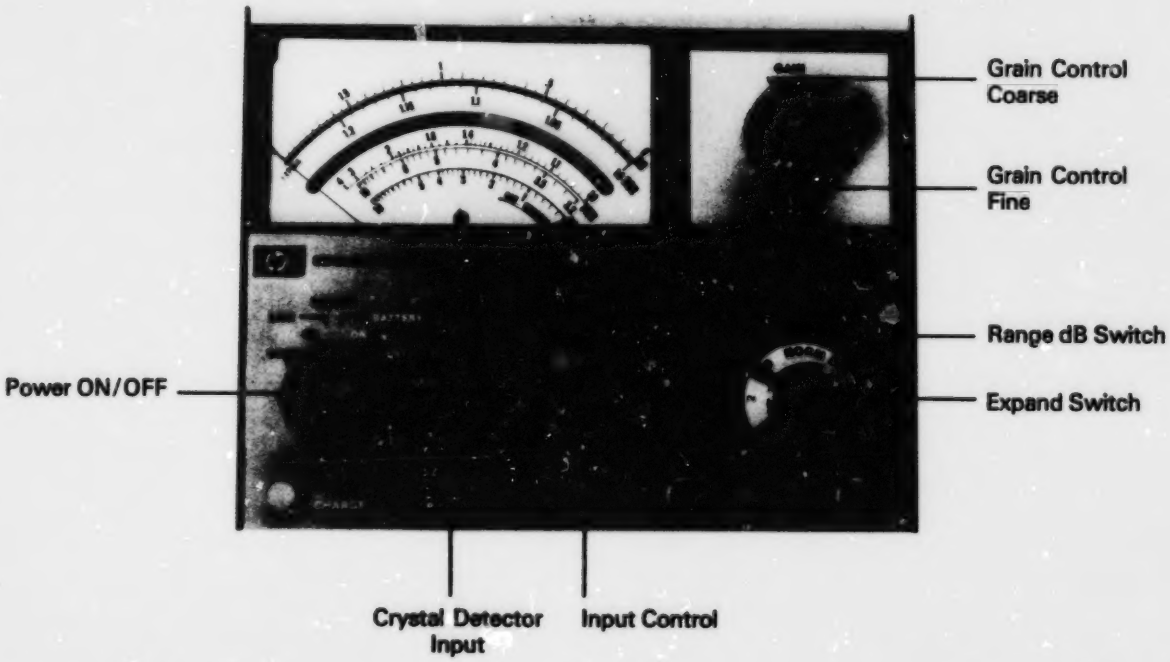


Figure A-5. Hewlett Packard standing wave ratio meter model 415E

4. Set the RANGE-DB switch to the 20 dB position and the EXPAND switch to the NORMAL position.

5. Set the GAIN and VERNIER controls to mid position.

6. Set up Hewlett Packard 8673A signal generator for a frequency of 2.880 GHz and a power level of −20 dBm (refer to section 3.2.3.2).

7. Slowly increase probe depth until a reading is obtained. Tune the probe to obtain a maximum reading by adjusting the tuning slider and the tuning wheel. Reduce the depth of the probe to such a depth that there is a mid-scale reading. Maximize the reading by retuning the probe and adjusting the modulation frequency on the signal generator.

8. Adjust slotted-line carriage for a maximum meter deflection. Change RANGE-DB switch and GAIN ccntrol if necessary to maintain an on-scale meter indication.

9. Readjust the GAIN and VERNIER controls for a full scale deflection (should read 1.0 on the 1.0 to 4.0 SWR scale).

10. Check the square law response of the detector. Reduce RF signal level if necessary.

11. Move the slotted-line carriage until a minimum is found. SWR's of 1 to 3.2 can be read directly from the upper numerals on the center scale. If the meter indication is left of scale, rotate RANGE switch one position clockwise. Read the SWR on the 3.2 to 10 scale. If the meter is still left of scale, rotate the RANGE switch one more position clockwise and read the SWR value from the 1.0 to 4.0 scale and multiply by 10 to give you the proper SWR.

12. The EXPAND switch can be used to read SWR's less than 1.25 with greater accuracy. Turn the EXPAND switch to the 0 dB position and read the SWR value directly off the 1.0 to 1.24 scale.

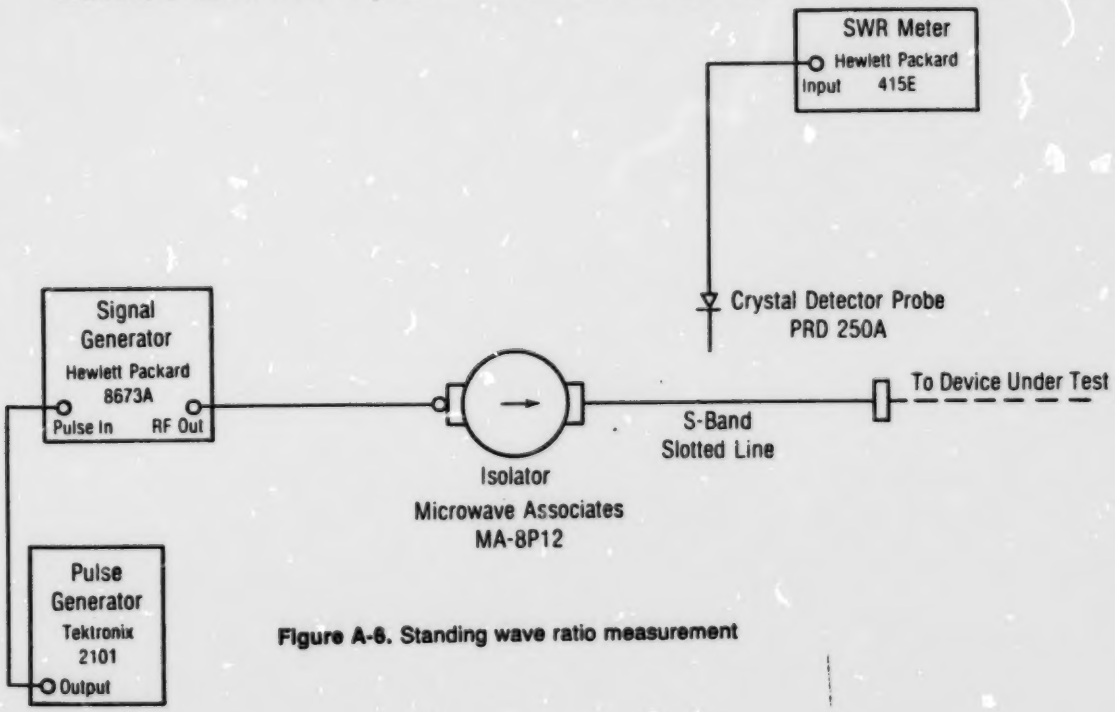


Figure A-6. Standing wave ratio measurement

For more detailed information please refer to the equipment manual.

A-II-ii-d. VHF Oscillator

RF Unit Hewlett Packard Model 3200B (AR0002)
This signal generator is a broadband RF oscillator operating from 10 to 500 MHz. The maximum output power level ranges from 25 to 200 mW over the various frequency bands. Output level can be adjusted by a potentiomenter on the front panel or by a variable attenuator on the back panel. This unit is used to provide 30 MHz IF signals. Operation is discussed below. (Refer to Figure A-7).

CW Operation

1. Turn power on and let instrument warm up for 10 minutes.

2. Connect 50 ohm load to output on the back panel through a coaxial cable.

3. Set MODE switch to AM/CW. Adjust RF level control to obtain desired power level. It should be pointed out here that impedance mismatches (loads other than 50 ohms) will change the power level supplied to the load. For calibrated power levels it is suggested that a power divider or a coupler in conjunction with a power meter be used to monitor the forward power received by the load.

4. Select FREQUENCY RANGE as desired. Frequency should be monitored by a frequency counter through a coupler. Fine tune to desired frequency.

Amplitude modulation

1. Turn on oscillator as in CW operation and set MODE switch to AM/CW.

2. Connect modulating signal (200 Hz to 120 kHz) to AM/B+ MOD INPUT. A 20 volt RMS modulating signal is required to obtain a 30 percent modulation. Impedance of modulation input is 600 ohms.

For more detailed information please refer to the equipment manual.

A-II-ii-e. Sweep generator

Weinschel Sweep Oscillator Model 430A and RF Unit Model 433AE
The Weinschel signal generator can be swept from 5.2 to 10.4 GHz. A sweeping signal in a frequency band allows quick analysis of the frequency response of a device being tested instead of point by point measurements in the band. It is primarily used in standing wave ratio (SWR, also see Appendix A-II-ii-c) and insertion loss measurements.

1. Push POWER to on and let warm up for 10 minutes.

2. Set TRIGGER to AUTO, 1 kHz ⊓⊔ to OFF and the SWEEP FUNCTION to desired function as outlined below.

3. SWEEP TIME as desired. Low speed is required when power meters are used as detectors and when x-y recorders are used to record the results. MANUAL is used to setup the frequency sweep range and recorder input.

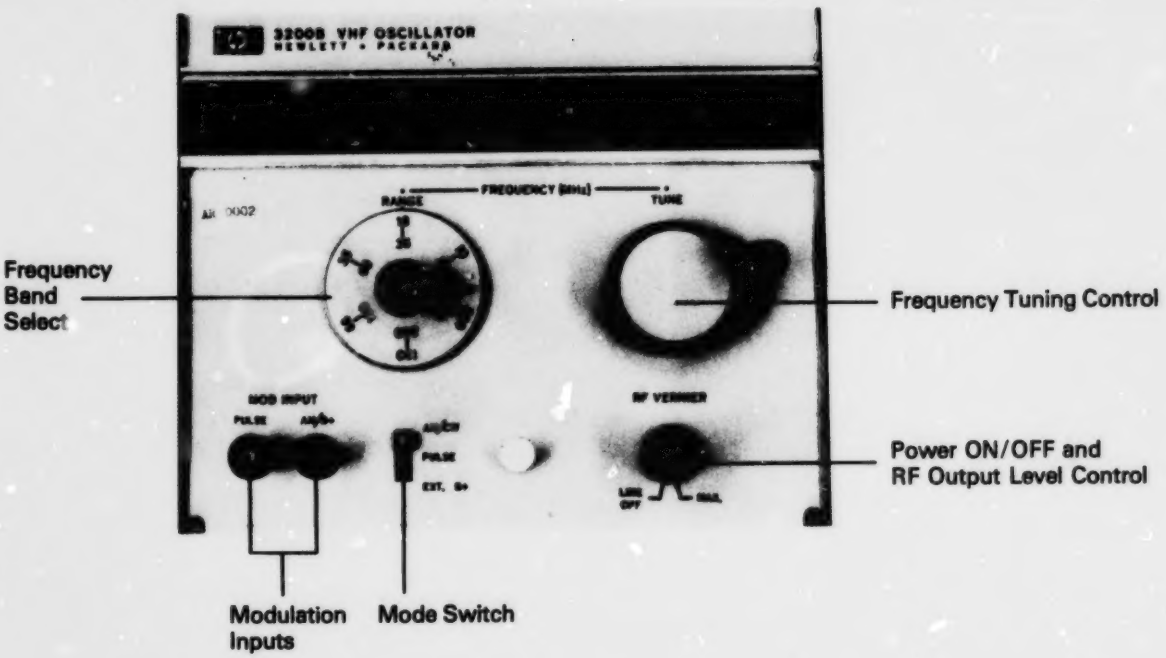


Figure A.7 Hewlett Packard VHF Oscillator Model 3200B

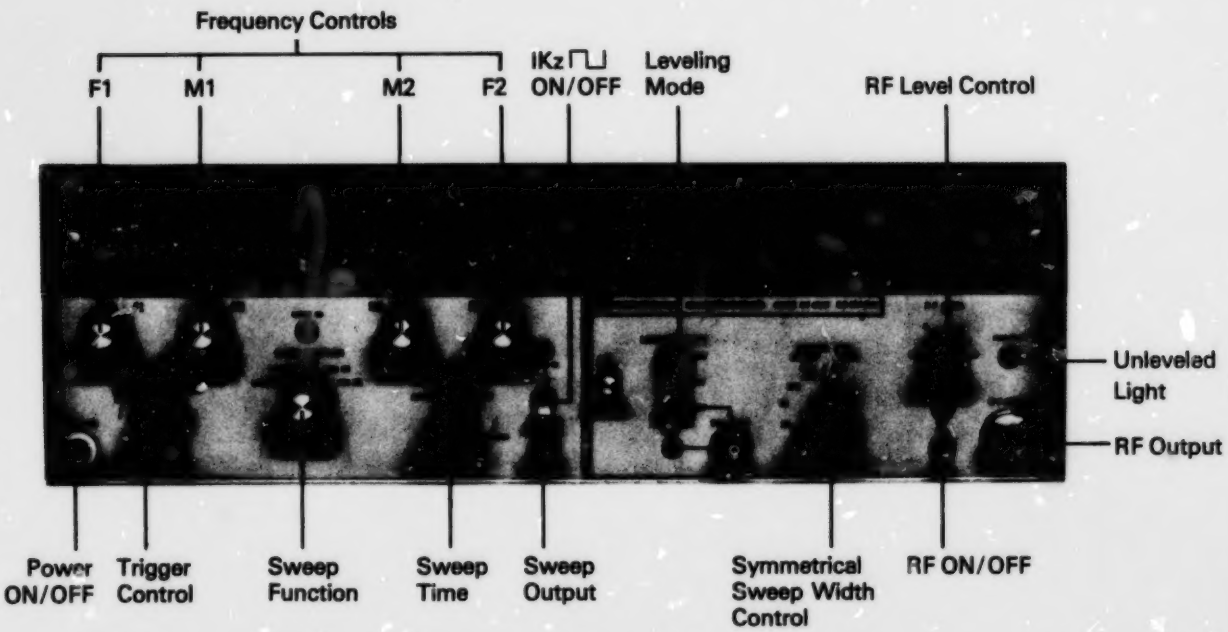


Figure A.8 Weinschel Sweep Oscillator Model 430A and RF Unit Model 433AE

4. Connect SWEEP OUT to recorder X input or scope external horizontal sweep input and adjust inputs to obtain optimum display sweep. Use MANUAL sweep control as necessary.

5. Switch RF to ON and press INT LEVEL button. Adjust RF LEVEL control to keep UNLEVELED light off.

6. Connect detector to RF output through a frequency meter (see Section 3.4). Check sweep frequency range as required. Adjust F1, F2, M1, and M2 controls as necessary. The sweeper is now ready for use.

There are three sweep functions available on the sweeper F1 to F2, M1 to M2, and Sym M1 sweeps.

F1-F2 Mode
With the SWEEP FUNCTION selector set to F1-F2, the output frequency sweeps within limits set by the F1 and F2 controls. Normally the low frequency limit is set by F1 and the high frequency limit by F2. However, F1 can be used to set the high limit and F2 the low limit. In all cases the unit sweeps between F1 and F2 commencing at F1.

M1-M2 Mode
The M1-M2 markers provide the means of selecting any portion of the F1-F2 frequency range for expanded display. With the SWEEP FUNCTION selector set to F1-F2 Mode, adjust the M1 and M2 controls to position the M1 and M2 markers at either side of the range to be expanded. Then, when the sweep function selection is switched to the M1-M2 mode, the frequency range established by the two markers is now the full width of the swept frequency display.

SYM-M1 Mode
Setting the SWEEP FUNCTION selector to SYM M1 and adjusting the M1 control to position the M1 marker to the desired frequency will cause the trace to sweep symetrically about the center frequency established by M1. The total sweep width (peak-to-peak excursion) is determined by the setting of the SYMETRICAL SWEEP WIDTH control located on the front panel of the RF Unit.

For more detailed information please refer to the equipment manual.

A-II-iii. Frequency domain

A-II-iii-a. Frequency counters

A basic frequency counter is used to count frequencies. A more sophisticated model may have the added capabilities of measuring time intervals, periods, events, and duty cycles, to name a few. Frequency counting will be the only function outlined in this manual. For other capabilities consult the technical manual.

There are two models of frequency counters in the radar trailer. Hewlett Packard model 5302A (AR0014) which is capable of measuring signals up to 50 MHz, and Hewlett Packard Model 5345A (AR0001) which is capable of directly counting up to 500 MHz and with the use of the Frequency Converter Model 5255A (AR0080), it is capable of counting from 2.6 GHz to 12.6 GHz.

Specifications
Frequency counters have both a minimum signal sensitivity with which they can count from and a maximum signal level with which they may de damaged. Both these levels must be observed to assure proper operation of the instrument.

Input safety limits of frequency counters

Model	Impedance	DC	Above DC
5345A	50 ohm X1	± 7 V	5 V RMS(27dBm) to 5 MHZ 3.5 V RMS(24dBm)above 5 MHz
	50 ohm X20	± 7 V	7 V RMS to 20 KHz
	1 Megohm X1	± 350 V	250 V RMS to 20 KHz 3.5 V RMS above 5 MHz
	1 Megaohm X20	± 350 V	250 V RMS to 20 KHz 70 V RMS above 5 MHz
5255A	50 ohm	± 5 V	0.7 V RMS(10dBm) pulse or average
5302A	1 Megohm	± 50 V	250 V RMS to 400 KHz 10 V RMS above 10 MHz

Hewlett Packard 5302A

This frequency counter is made up of two parts, called the Measuring System, model 5300A and the Frequency counter or Universal Counter, model 5302A. To measure continues wave (CW) signals with this counter follow the steps listed below (refer to Figure A-9).

1. Turn AC power on with the SAMPLE HOLD control and let warm up for 10 minutes.

2. Turn the FUNCTION switch to the CHECK position. The display should now read 10.0000 MHz ± 1 count to indicate all circuits are functioning properly.

3. Adjust the SAMPLE HOLD control for a convenient interval between measurements.

4. Set the FUNCTION switch to A or B depending on input channel used. Channel A will accept input signals from 10 Hz to 50 MHz and channel B will accept input signals from 10 Hz to 10 MHz. When selecting channel A the input signal is prescaled by 10. Since no prescaling occurs in channel B, higher resolution measurements can be made by using Channel B.

5. Set WAVE SHAPE switch to either sine wave, positive pulse or negative pulse depending on the input signal.

6. Set TIME BASE switch to the AUTO position for automatically setting the gate time needed to fill the display for maximum resolution.

7. Adjust SENSITIVITY control A or B to the fully counter-clockwise position for minimum sensitivity.

8. Connect input signal to be measured to the input channel selected.

9. Slowly adjust SENSITIVITY clockwise for a stable display.

10. Readjust the SAMPLE HOLD control to obtain a stable readout.

11. It may be necessary to press RESET to start the count.

12. Instrument display is the input signal frequency.

For more detailed information please refer to the equipment manual.

Hewlett Packard 5345A
To measure CW waveforms with the 5345A follow the steps listed below (refer to Figure A-10.):

1. Set POWER switch to ON position and let it warm up at least 10 minutes.
2. Set FUNCTION switch to FREQUENCY A.
3. Set DISPLAY POSITION switch to AUTO.
4. Set GATE TIME switch to give required integration time or desired resolution.
5. Set CHANNEL A Input Impedance switch to appropriate position.
6. Set CHANNEL A ATTEN switch to match input signal's amplitude (refer to Input safety limit listing for maximum input levels).
7. Set CHANNEL A LEVEL control to start measurement at desired voltage level. Use the PRESET position for sine waves.
8. Set CHANNEL A Coupling switch to AC or DC (refer to Input safety limit testing for input specifications).
9. Set Input Amplifier Control switch to SEP.
10. Set back panel Gate Control switch to INTERNAL position for normal operation.
11. Connect input signal to CHANNEL A input jack.
12. Adjust SAMPLE RATE control for a convenient interval between measurements.
13. It may be necessary to press RESET to start the count.
14. Instrument display is the input signal frequency.

Frequency Converter — Hewlett Packard 5255A (AR0080)
The 5255A is a plug-in module to the 5345A which extends the frequency measuring capability to a range of 2.6 GHz to 12.6 GHz.

To operate the 5255A follow these steps (refer to figure A-11):

CW Measurement
1. Connect input signal to input of converter.
2. Set Mixing Frequency control to read slightly less than 2.8 GHz.
3. Slowly turn Mixing Frequency control counter-clockwise to obtain the first response, and tune for a maximum reading in the green portion of the Level Indicator Meter scale.

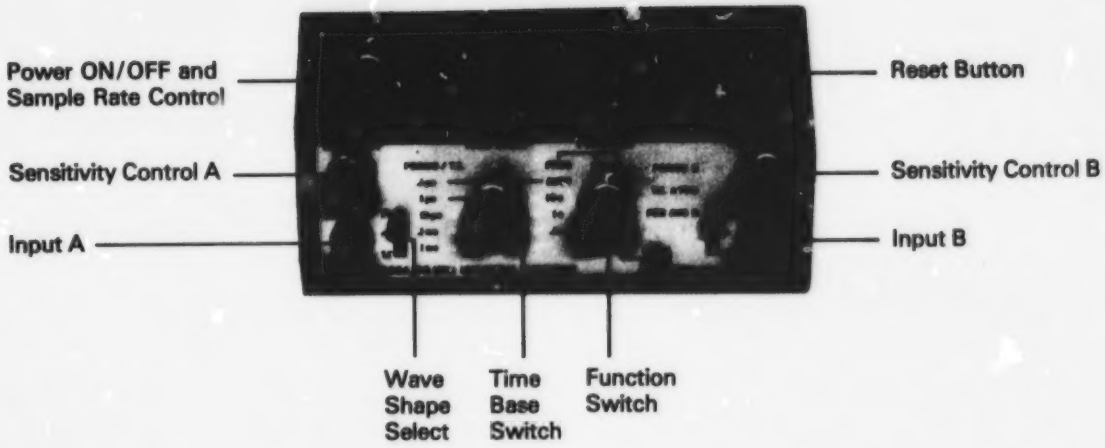


Figure A-9 Hewlett Packard Frequency Counter Model 5302A

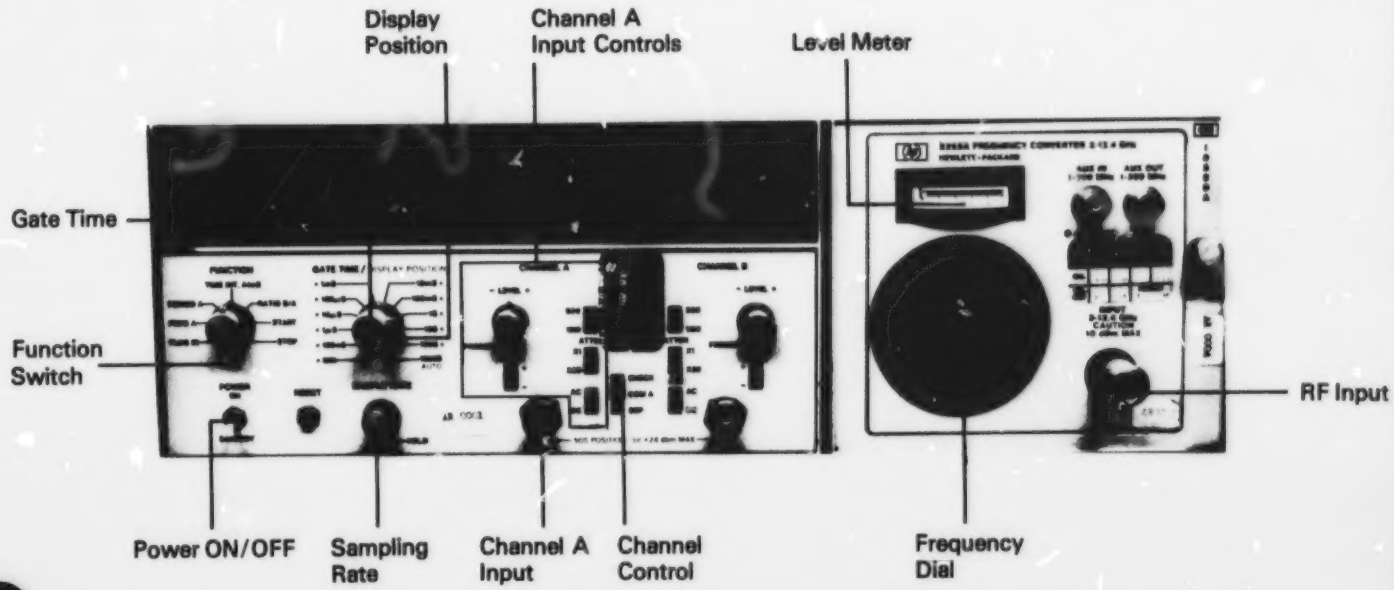


Figure A-10 Hewlett Packard Frequency Counter Model 5345A and Frequency Converter Model 5255A

4. Add frequency counter display (in MHz) to Mixing Frequency control reading (in GHz) for frequency of INPUT signal.

5. To double check the reading, continue to turn the FREQUENCY dial counter-clockwise until the needle is again in the green region, the frequency is now equal to the frequency counter display (in MHz) subtracted from the Mixing Frequency control (in GHz). The reading in step five should equal the reading obtained in step four.

Pulsed RF

RF pulses are not as easily counted as CW signals since the signal exists only part of the time. The counter thus must be synchronized externally so the measurement will be taken only when the signal is present. The counter will define frequency in terms of the average number of cycles that occurred during its measurement interval, so the answer will vary depending on the length of the measurement and where within the RF pulse the measurement is made.The RF pulse may have undesirable frequency transients at the beginning and end which are not representative of the frequency present during the body of the pulse. These errors become even more significant when narrow RF pulses are being measured since the time during which transients are present becomes a greater percent of the pulse width. Changes in frequency from pulse to pulse may also occur.

To measure pulsed RF signals follow these steps:

1. Set up test configuration as indicated in figure A-11.

2. Set the Pulse Generator for a time shorter than the pulse width of the RF burst for a valid measurement. This pulse must go low (-1 volt) to start the measurement and go high (0 volt) to stop it.

3. For increased resolution set the GATE TIME on the 5345A for longest available time but still less than the pulse width.

4. Tune the 5255A by observing the AUX OUTPUT signal on the oscilloscope and by adjusting the MIXING FREQUENCY CONTROL so the frequency of the convertor's local oscillator is less than 100 MHz away from the RF input signal. For example, the C-Band radar input is 5.635 GHz, the convertor's frequency should be between 5.535 GHz and 5.635 GHz for a correct indication.

5. Add attenuation to the RF input signal if necessary to get a signal level which is neither too high as to overload the video amplifier and create a distorted pulse or too small has to have a poor signal to noise ratio. A level of between -5 to -10 dBm peak should be sufficient.

6. Read the frequency of the RF pulse on the frequency counter.

7. It maybe necessary to add a high pass filter or band pass filter at the RF input too the 5255A to prevent pulse modulator feedthrough from saturating the video amplifier of the plug-in.

For more detailed information please refer to the equipment manual.

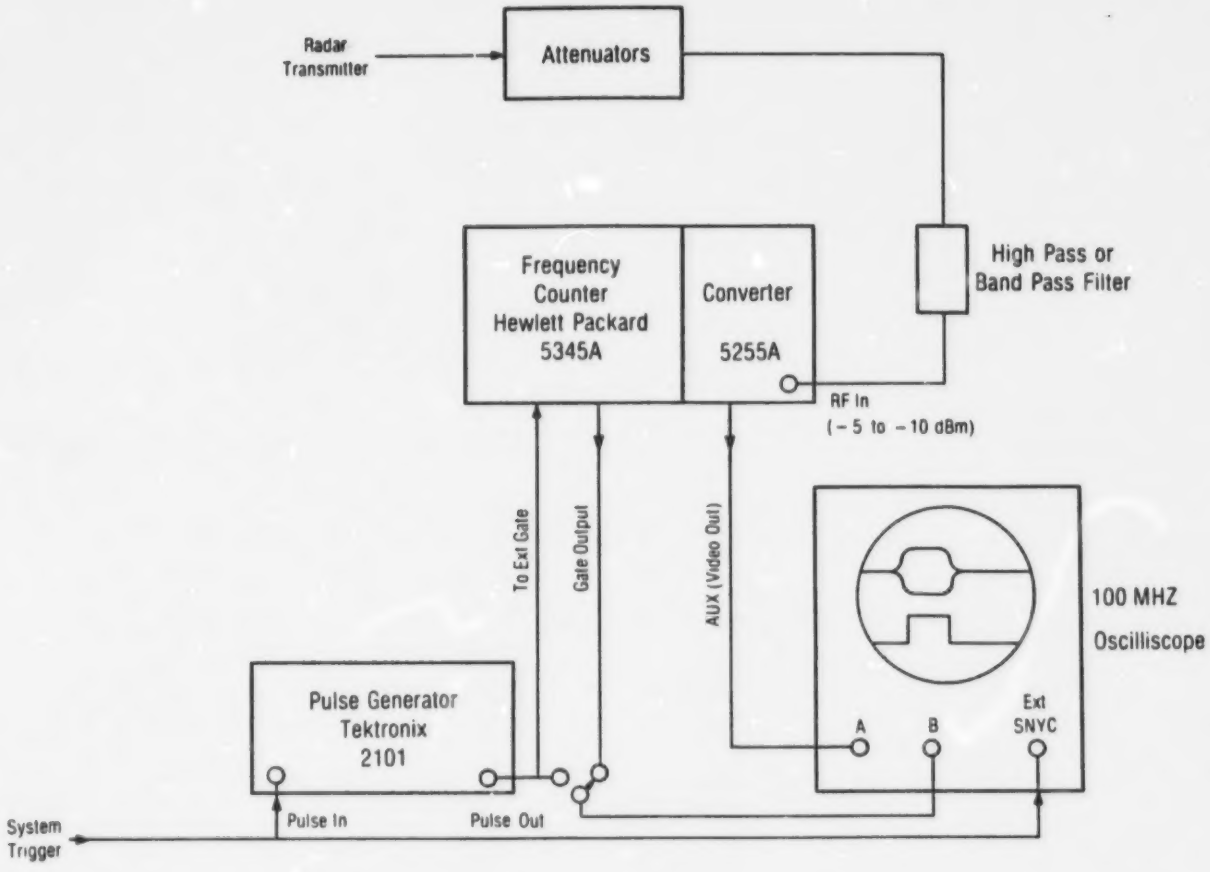


Figure A-11. Pulsed RF measurement set-up

A-II-iii-b. Signal generators

Hewlett Packard synthesized signal generator model 8673A
The generator will be used primarily to calibrate pulsed radar systems.

The characteristics of the HP Synthesized Signal Generator 8673A are:

Frequency Range:	2.0 GHz to 26 GHz
Output Calibrated from:	+7dBm to -100 dBm
Leveled output:	+7dBm to -100 dBm 2.0 to 18.0 GHz
	+2dBm to -100 dBm 18.0 to 22.0 GHz
	-2dBm to -100 dBm 22.0 to 26.0 GHz

Note: the signal generator is not calibrated for output levels above +7dBm. Spurious oscillations may occur above this level.

Pulse Modulation

Damage level:

More positive than +6 volts from less than 50 ohm source or more negative than −0.5 volts peak from a 50 ohm source.

External drive is required for all modulation modes.

Pulse input:

Normal Mode	> 3.0 V ON < 0.5 V OFF	
Complement mode	< 0.5 V ON > 3.0 V OFF	
On/off ratio:	> 80 dB	auto peak enabled
Rise and Fall time:	< 35 nsec.	auto peak enabled
Pulse Repetition Frequency:	DC to 1MHz	auto peak enabled
Minimum Pulse off time:	<300 nsec.	
Maximum Delay time:	150 nsec.	

These operating instructions are normally not needed for radar system calibrations. They are included here for completeness and should be used with instructions in Section 3.2.3.2.

Values for SWEEP FRQ (START, STOP, △F, and MKR) and SWEEP RATE (STEP and DWELL) are entered in a Function-Data-Unit format.

Sweep frequency

The SWEEP FREQ keys set the span of the sweep (that is, the range that the sweep covers). The sweep span can be set with either the START and STOP keys or with the FREQUENCY and △F keys.

Sweep rate

During a sweep, the Signal Generator changes frequency in discrete steps. Sweep rate is determined by the number of steps and the dwell time. The number of steps can be set in either of two ways.

To set the number of steps to be used in a sweep press STEP, use the numeric keys to enter the number of steps, then press STEPS(ms).

The sweep span is divided by the number of steps to determine the step size.

To set the step size, press STEP, use the numeric keys to enter the frequency of the step, then press GHz or MHz or kHz.

The sweep span is divided by the step size to determine the number of steps.

The dwell time determines how much time elapses before the next frequency step is taken.

To set the dwell time press DWELL, use the numeric keys to enter the time in milliseconds, then press STEPS(ms).

Sweep mode

To start a sweep press:

1. AUTO for a repetitive sweep.

2. MANUAL for a sweep that is controlled by the TUNE knob or the FREQ INCREMENT Up and Down keys.

3. SINGLE for one sweep only. Press this key once to tune the Signal Generator to the start frequency. Then, press this key again to actually initiate the sweep.

4. To stop a sweep, in any mode, press OFF.

Setting output level
The output level is set with the RANGE and VERNIER controls.

First press the RANGE buttons to step the output level down or up by increments of 10 dB. The selected range is shown in the RANGE dBm display.

Then, press LVL MTR to select OUTPUT LEVEL VERNIER to be displayed on the meter. Adjust RANGE VERNIER between −10 and +3 dB, as read on the meter.

The output level is determined by adding the meter display to the RANGE dBm display.

To maintain output power at a constant level press ALC INTERNAL.

Press AUTO PEAK to maximize power at the output frequency, to minimize power of spurious signals and to optimize pluse shape for pluse modulation.

Store/Recall
Up to nine front panel settings can be stored for later use. All Signal Generator front panel functions can be stored, although OUTPUT LEVEL VERNIER is stored in remote mode only.

1. STO 3 stores a front panel setting in register 3.

2. RCL 4 recalls a front panel setting stored in register 4 and changes the output of the Signal Generator to the recalled parameters.

Modulation
Three types of modulation are available: amplitude (AM), frequency (FM), and pulse. Each type requires an external drive signal. Front panel keys select the maximum percent of AM, FM deviation in MHz, and normal (NORM) or complement (COMPL) pulse mode. For AM and FM, a 1 V peak signal develops full scale modulation. Modulation varies linearly with the input signal. For pulse modulation, a TTL level positive-true pulse turns RF on in normal mode. A TTL level negative-true pulse turns RF on in complement mode.

Messages
Entry errors, hardware malfunctions, and other significant conditions are indicated by the lighted MESSAGE key.

Press MESSAGE to read the two-digit code in the FREQUENCY MHz display. The codes are explained in the equipment manual and on the operating information pull-out card.

Simplified operation

Presetting Front Panel

Press RCL 0 to set the front panel to the following conditions:

RF OUTPUT	to	ON
ALC INTERNAL	to	ON
RANGE	to	– 70 dBm
AUTO PEAK	to	ON
Meter Scale	to	LLVL
AM, FM, and PULSE Modulation	to	OFF
FREQUENCY	to	3000.000 MHz
FREQ INCR	to	1.000 MHz
START	to	2000.000 MHz
STOP	to	4000.000 MHz
△F	to	2000.000 MHz
MKRS	to	OFF (initialized to 5,10,15,20, and 25 GHz)
SWEEP MODE	to	OFF
STEP	to	100 steps (20.000 MHz)
DWELL	to	20 ms
TUNE Knob	to	ON

Frequency

Frequency and frequency increment values are set in a Function-Data-Units format.

For example, to set frequency to 4.5 GHz and frequency increment to 500 MHz:
press FREQUENCY — 4.5 – GHz
press FREQ INCR — 500 – MHz
Frequencies may be entered in GHz, MHz, or kHz, but are always displayed in MHz.

To change the current frequency by the selected increment value, use: Freq Incr UP/DOWN keys or the TUNE knob.

For more detailed information please refer to the equipment manual.

A-II-iii-c. Spectrum analyzer

The Hewlett Packard Spectrum Analyzer consists of a RF section model 8555A (AR0076), IF section model 8552B (AR0077) and a Display Section model 141T (AR0078).

Specifications

The spectrum analyzer is susceptible to damage by excessive input power. The maximum power rating marked on the input peak power must be calculated before the RF is connected. Extra attenuators may be necessary for its protection. An RF limited, model 1169A is available to safeguard the analyzer against any unexpected surges. This limiter has a threshold level, that whenever exceeded, limits the RF signal applied to the spectrum analyzer to a pre-set value (+ 7 dBm). Unwanted harmonics may be generated when in this limiting mode.

Control signals to the spectrum analyzer, exceeding input specifications are also dangerous. For complete specifications consult the reference manual.

RF section Model 8555A

Frequency Range:	10 MHz to 40 GHz.
MAX POWER to RF INPUT:	+33 dBm average or peak with input attenuator set at 30 dB or greater.
MAX POWER to MIXER INPUT:	+10 dBm average or peak.

RF Limiter Hewlett Packard Model 11693A

Frequency Range:	100 MHz to 12.4 GHz
MAX INPUT POWER:	+30 dBm average
	+48 dBm peak (pulse width < or = to 1 us)
Limiting Threshold:	+7 dBm

Note: Operating procedures have been included in Section 3.2.3.3.1 for the HP system and in section 3.2.3.3.2 for the TEXTRONIX 492P system.

For more detailed information please refer to the equipment manuals.

Appendix B: Theory

B-I. Electronics

B-I-i. Radar

B-I-i-a. Basic fundamentals and applications of radar (Varian)

A complete copy of the document is included at the end of the manual.

B-I-ii. S-Band antenna

Introduction

The S-band radar is capable of transmitting elliptically polarized signals at any chosen axial ratio and orientation. Elliptical radiation can be resolved into two circular components whose phase relationship determines the orientation of the elliptical wave. This is illustrated in figure B-1.

If the two components are equal in amplitude, linearly polarized radiation is obtained. The variable polarization is produced through the utilization of microwave circuitry housed near the antenna dish.

Description of the microwave circuitry

The heart of the antenna is the turnstile located in front of the antenna dish (Refer to figure B-3). The turnstile is basically a rectangular wave guide to circular wave guide coupler with two inputs. The lower waveguide signal is radiated as left hand circular (LHC) signal and the upper as right hand circular (RHC) signal. When there are signals into both waveguides, the two circular waves are combined into an elliptical wave. If these signals are equal, a linearly polarized wave is transmitted. A turnstile is a bidirectional device and thus elliptical signals received by the antenna are resolved into two circular components called main and orthogonal components. These are received by two separate receivers (port 2 and port 1).

The rest of the microwave circuitry is in the pedestal's upper box located behind the antenna dish. The microwave circuitry directs high power RF from the transmitter into the antenna turnstile and directs low power RF from the antenna turnstile into the receivers. The components of the microwave circuitry are described below (refer to figure B-4).

1. Phase shifter — controls the relative length of the left-hand circular waveguide to the turnstile, changing the relative phase between the left-hand circular and right-hand circular signals, hence the orientation of transmitted and received ellipical waves.

2. Duplexer — an electronic switch that alternately connects the antenna to the transmitter or to the receiver, protecting the receiver from high power transmitted pulses. The unit normally consists of ATR (anti-transmit/receive) cells and a passive TR cell.

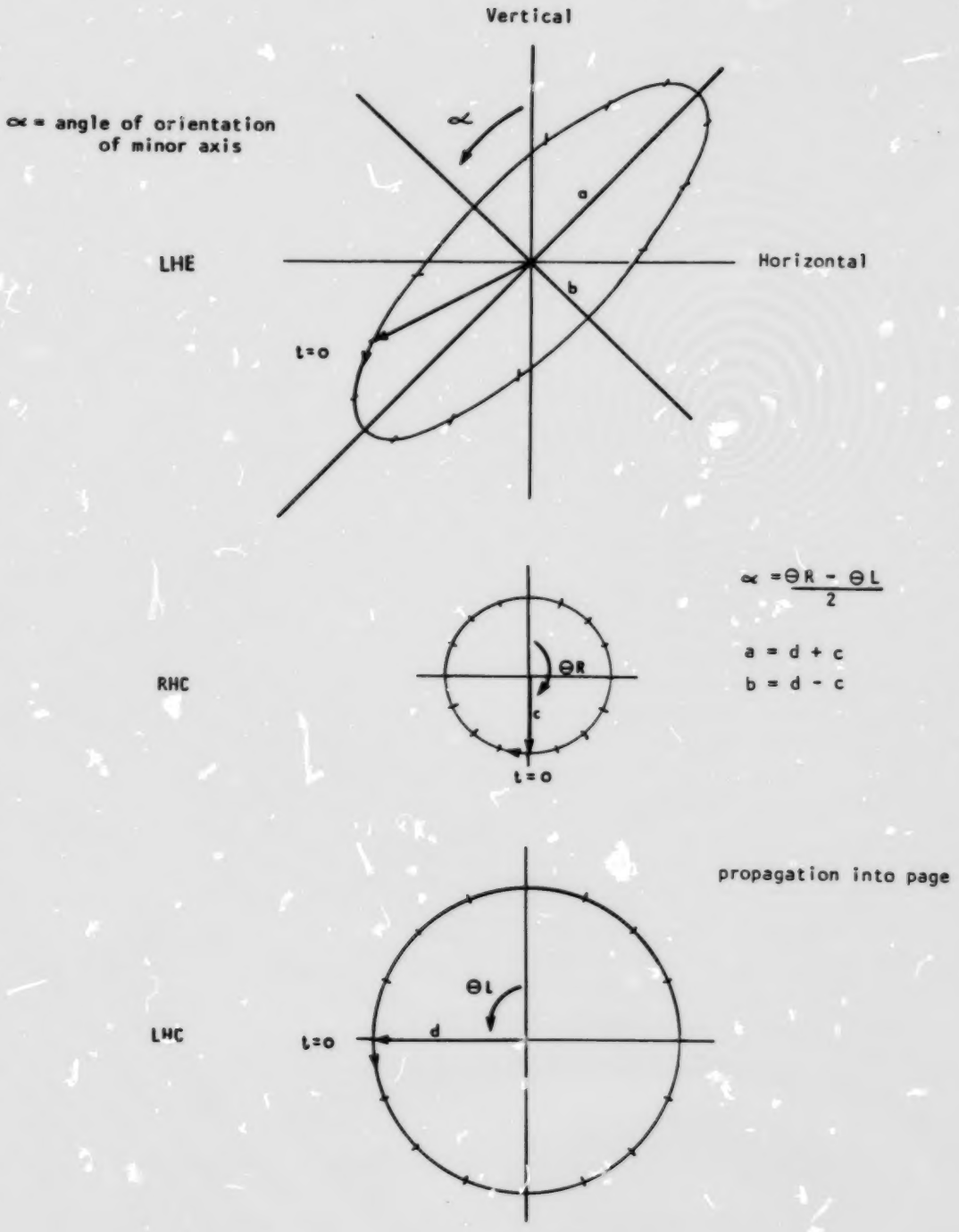


Figure B-1. An elliptically polarized wave and its circular components

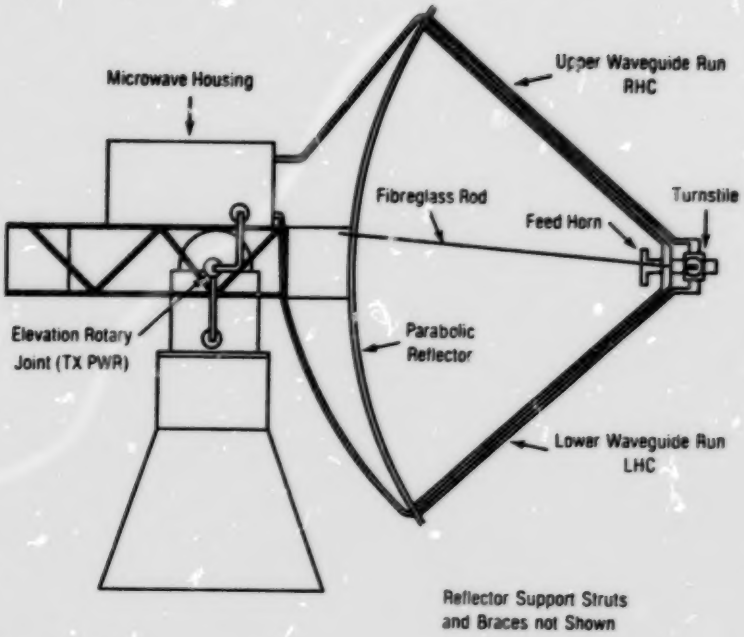


Figure R-2. The S-Band antenna

3. 3 dB Hybrid (Quadrature Hybrid) — a four-port, 3 dB coupler capable of splitting an input signal into isolated quadrature phased outputs. Quadrature hybrids are symmetrical networks; signals applied to any port will split equally between the opposite port pairs, with the adjacent port remaining isolated. A signal applied to one port will split equally between both opposite ports, with a 90 degree phase difference (voltage reference). If the opposite ports are properly terminated, substantially all of the signal applied to the input port is absorbed in the loads. The adjacent port, therefore, will "see" virtually none of the incident signal and is therefore isolated. For two hybrids connected in series (figure B-5), the signal into port A will appear at C, B at D, D at B, C at A respectively.

4. Polarization Control — two "E plane tees" control the impedances of the waveguide junctions between the 3 dB hybrids. The "E plane tees" have plungers which are moved by motors, and the depths of these plungers are indicated by the polarization dial on the Polarization and Phase Controller. At a dial reading of 63200 the tees are matched, at 59403 the tees are infinitely mismatched (all power reflected), and at 58525 half the signal is passed and half is reflected.

5. Feedhorn — a waveguide to freespace matching device.

6. Rotary Joints — waveguide devices which allow two waveguide flanges freedom to rotate independently in one axis without affecting waveguide parameters, such as VSWR.

7. Isolator — used for protection from large mismatches between the hybird assembly and the port 2 receiver protector.

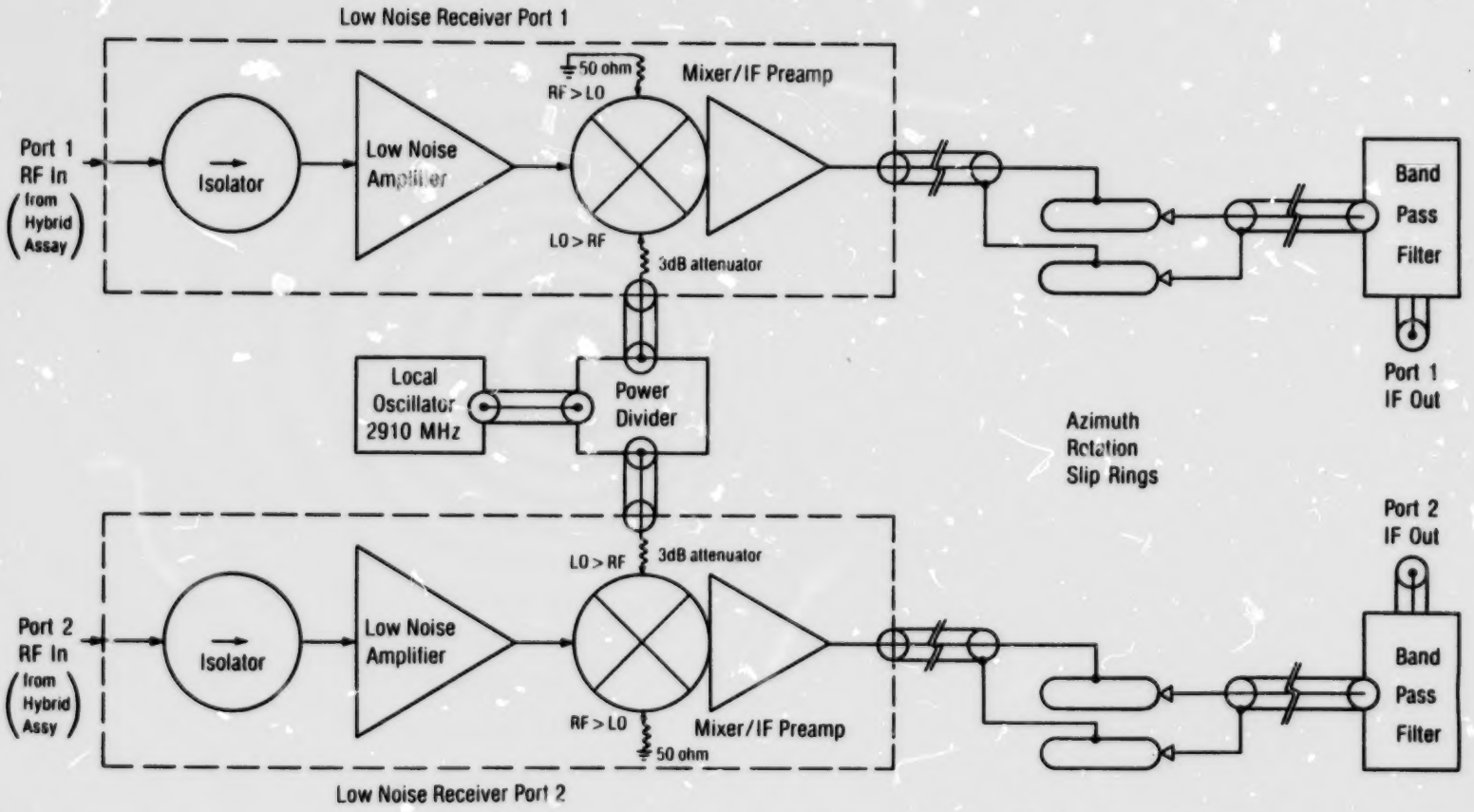


Figure B-3. S-Band antenna microwave block diagram

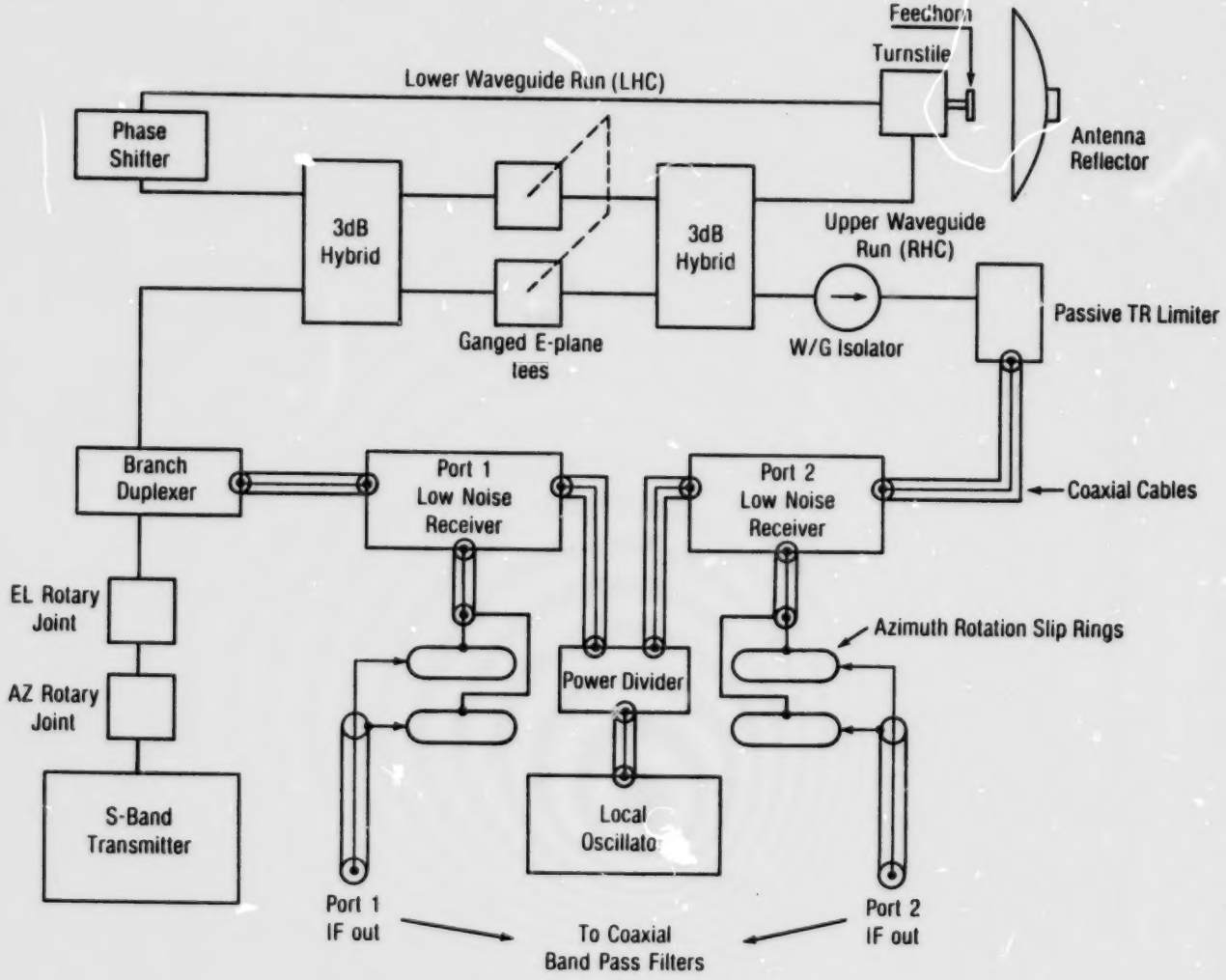


Figure B-4. S-Band receiver block diagram

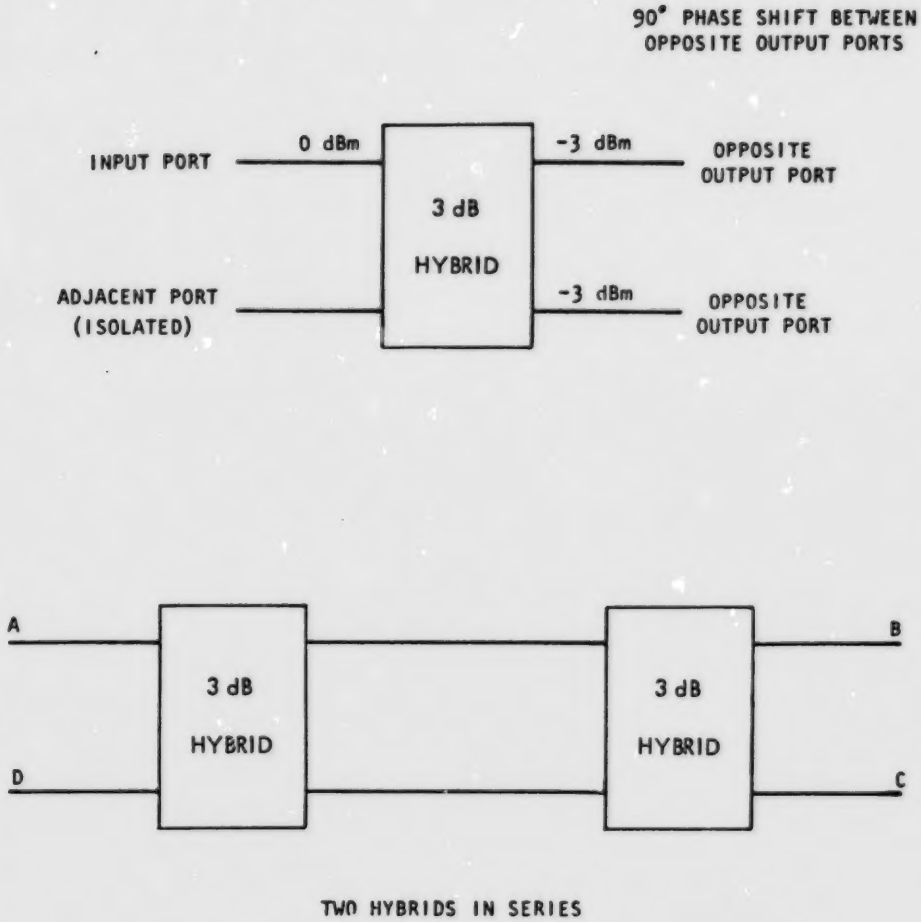


Figure B-5. 3 db hybrids

Theory of operation

When the microwave circuitry is connected as shown in figure B-4, the E plane tees are used as variable power dividers. When set at 59403, the radar pulse is directed to the lower waveguide run and a LHC polarized radiation is transmitted. When set at 63200 the pulse is directed to the upper waveguide and a RHC wave is transmitted. When set at 58525, the power is split equally in the two waveguides and a linear signal is radiated. The orientation of this linear signal is controlled by the phase control. For a vertically polarized signal, the phase control is set to zero. For a horizontally polarized signal, the phase control is set to 180 degrees.

The radar is usually set to transmit a left hand circular wave with the polarization control at 59403 and the phase control at 0 degrees.

During major calibration procedures, the polarization control is set at linear (dial reading 58525) such that the signal injected into the lower waveguide run is divided equally into the two receivers.

In antenna and phase discriminator calibration procedures, the polarization control is used to direct the signal from the monitor to appropriate receiver ports. Isolations and signal to noise ratios of the receivers are then measured. The phase control is used to check the performance of the phase detector.

On reaching precipitation (hydrometers) the microwave radiation from the transmitter is scattered. The polarization of the scattered radiation is dependent on the shape of the precipitation. This is shown in figure B-6 together with the signals and their phase relationship expected at the two receivers. This is an over-simplified case because there is more than one hydrometer and they are constantly in motion. These factors, however, do not significantly affect the signal expected at the receivers if they have the same preferred orientation. If only a portion of the particles have preferred orientations a noisy constant phase signal is received. If the orientation is completely random the phase signal is pure noise.

Circular depolarization ratio (CDR) is a measurement of the shape of the particles in a storm. Mathematically:

$$\text{CDR (dB)} = 10 \log_{10} \frac{\text{power at port 1}}{\text{power at port 2}} = \text{power at port 1 (dB)} - \text{power at port 2 (dB)}$$

For spherical particles the CDR will be small compared to the CDR of deformed particles.

Reflectivity (Z) is related to the reflected power at port 2 (Pr) by the following equation:

$$Z\,(dB) = M + 20\,\text{LogR} + Pr + L - Pt$$

where:
- M = radar constant (dB)
- R = range (km)
- Pr = received power (dBm)
- L = total atmospheric loss to the target and back (dB)
- Pt = transmitted power (dBm)

Figures B-7, B-8, B-9, B-10, and B-11 indicate axial ratios versus plunger settings, orientation of the polarization ellipse, and antenna patterns respectively.

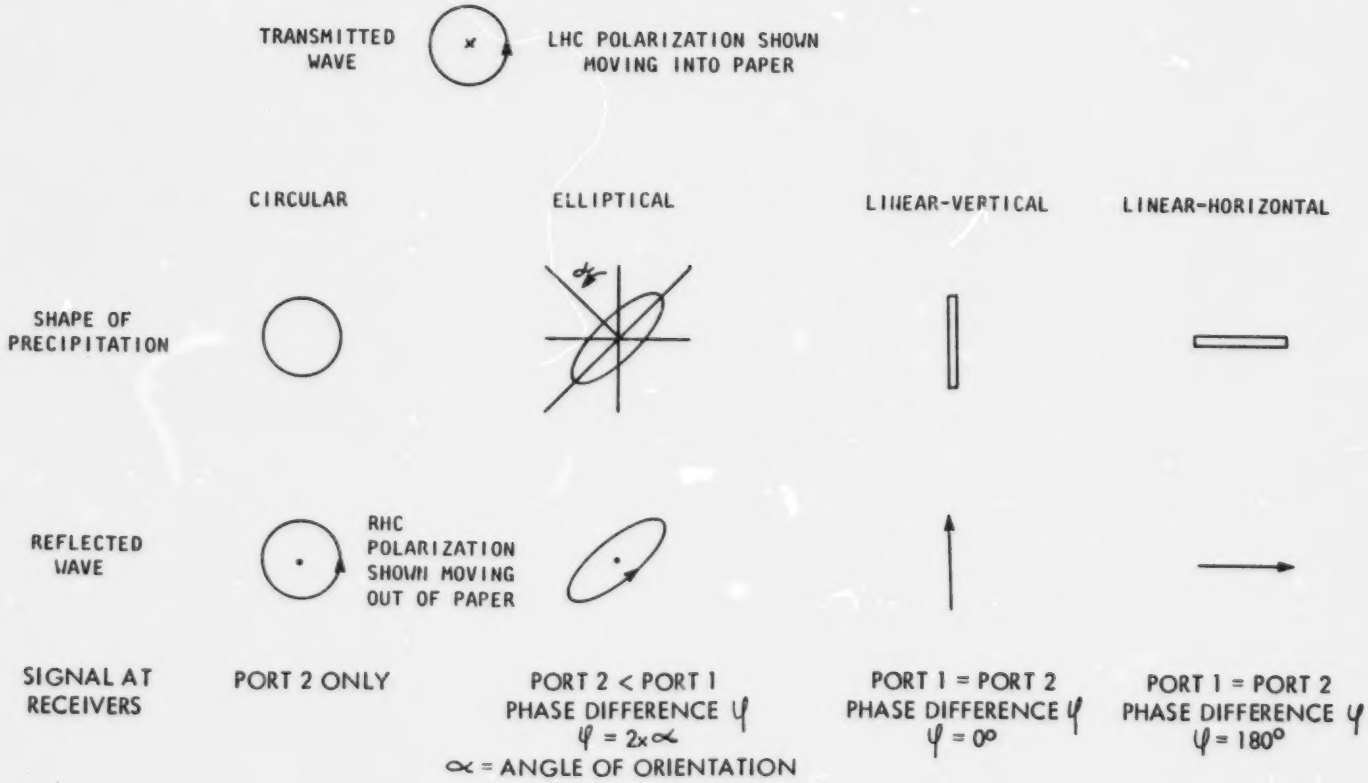


Figure B-6. Scattered signal from storm particles

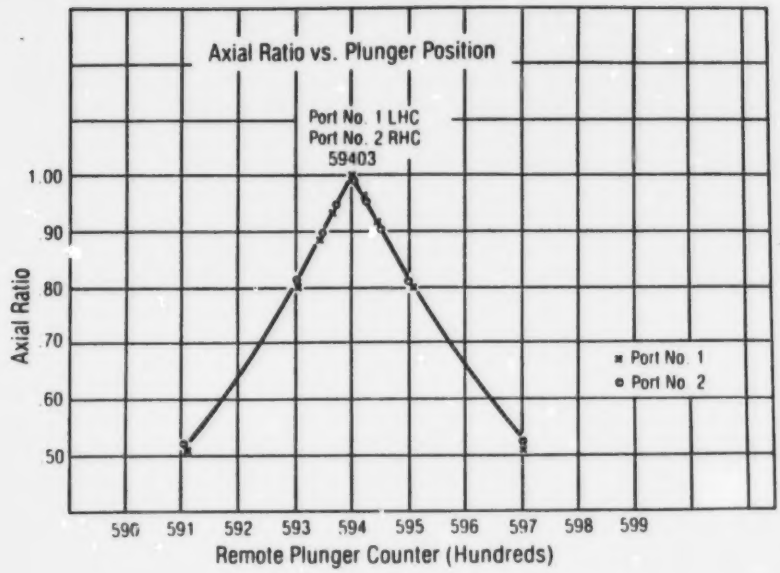


Figure B-7. Axial ratio versus plunger setting

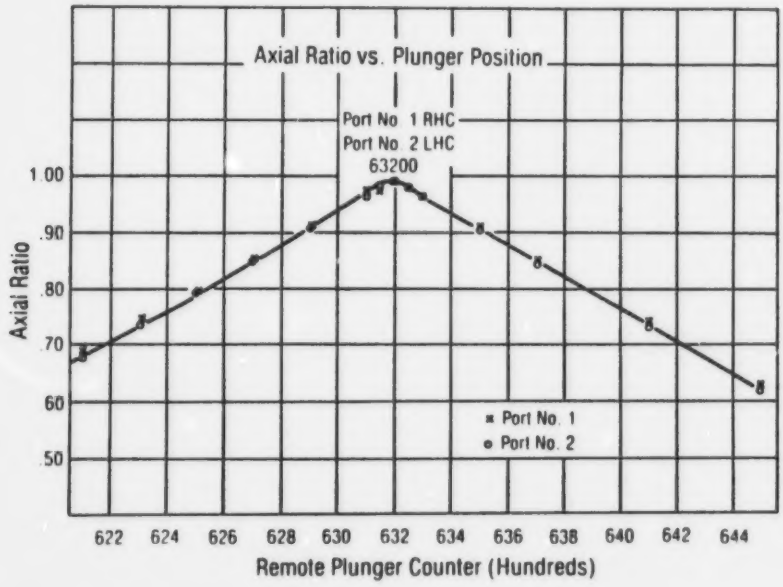


Figure B-8. Axial ratio versus plunger setting

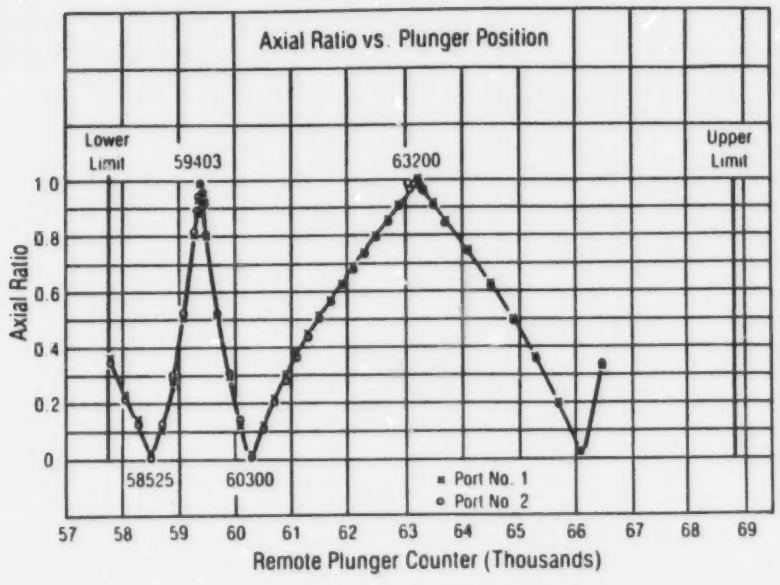


Figure B-9. Axial ratio versus plunger setting

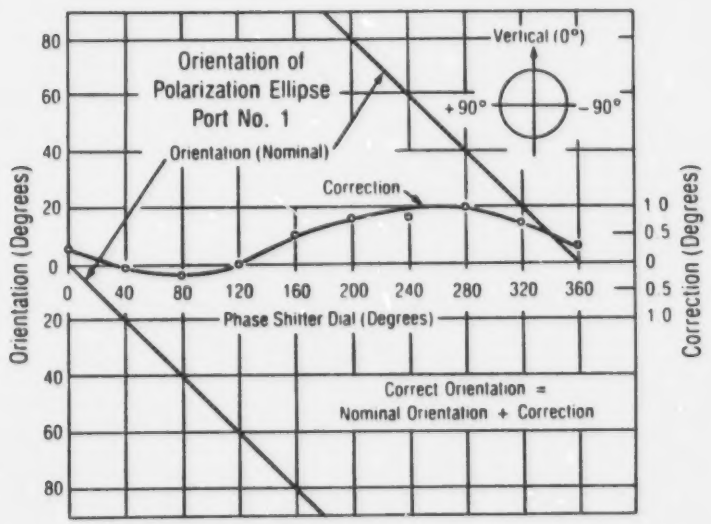


Figure B-10. Orientation of the polarization ellipse

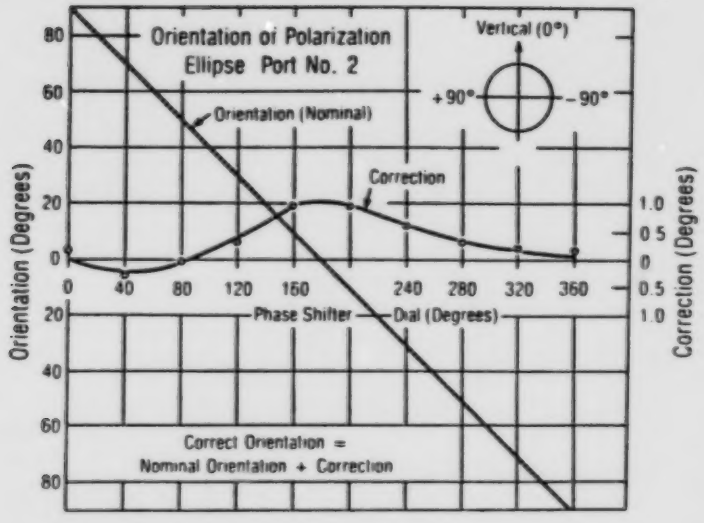


Figure B-11. Orientation of the polarization ellipse

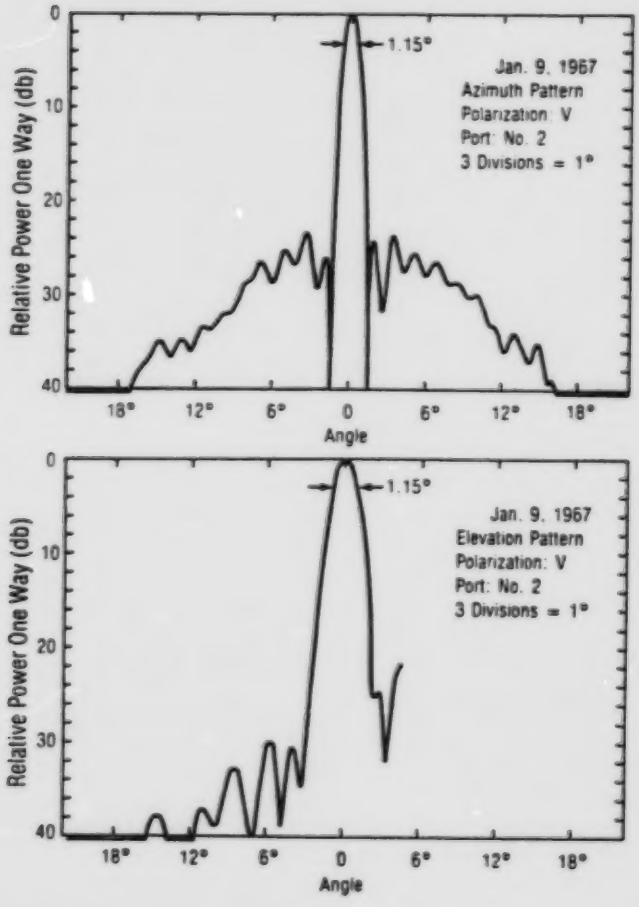


Figure B-12. Azimuth and elevation patterns

B-II. Measurements and tests

B-II-i. XYZs of using a scope

A complete copy of this document is included at the end of the manual.

B-II-ii. Spectrum analysis

A copy of the two HP applications notes #150 and #150-2 are included at the end of the manual.

THE XYZs OF USING A SCOPE

Tektronix
COMMITTED TO EXCELLENCE

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INTRODUCTION

If you watch an electrical engineer tackling a tough design project, or a service engineer troubleshooting a stubborn problem, you'll see them grab a scope, fit probes or cables, and start turning knobs and setting switches without ever seeming to glance at the front panel. To these experienced users, the oscilloscope is their most important tool but their minds are focused on solving the problem, not on using the scope.

Making oscilloscope measurements is second nature to them. It can be for you too, but before you can duplicate the ease with which they use a scope, you will need to concentrate on learning about the scope itself: both how it works and how to make it work for you.

The purpose of this primer is to help you learn enough about oscilloscopes and oscilloscope measurements that you will be able to use these measurement tools quickly, easily, and accurately.

The text is divided into two parts:

The first four chapters of Part I describe the functional parts of scopes and the controls associated with those parts. Then a chapter on probes concludes the section.

Part II allows you to build on the knowledge and experience you gained from Part I. The signals you'll see on the screen of an oscilloscope are identified by waveshape and the terms for parts of waveforms are discussed. The next two chapters cover safety topics and instrument set-up procedures.

Then Chapter 9 describes measurement techniques. Exercises there let you practice some basic measurements, and several examples of advanced techniques that can help you make more accurate and convenient measurements are also included. The last chapter in this primer discusses oscilloscope performance and its effects on your measurements.

Having a scope in front of you while working through the chapters is the best way to both learn and practice applying your new knowledge. While the fundamentals will apply to almost any scope, the exercises and illustrations use two specific instruments: the Tektronix 2213 and 2215 Portable Oscilloscopes. The 2213 is a dual-channel, 60 MHz portable designed as an easy-to-use, lightweight, general-purpose oscilloscope. The 2215 is a dual time base oscilloscope with more features and capabilities; it's included so you will understand dual time base scopes and appreciate the additional measurement capabilities they offer.

If you have comments or questions about the material in this primer, please don't hesitate to write.

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PART I. SCOPES, CONTROLS, & PROBES

You can measure almost anything with the two-dimensional graph drawn by an oscilloscope. In most applications the scope shows you a graph of voltage (on the vertical axis) versus time (on the horizontal axis). This general-purpose display presents far more information than is available from other test and measurement instruments like frequency counters or multimeters. For example, with a scope you can find out how much of a signal is direct, how much is alternating, how much is noise (and whether or not the noise is changing with time), and what the frequency of the signal is as well. Using a scope lets you see everything at once rather than requiring you to make many separate tests.

Most electrical signals can be easily connected to the scope with either probes or cables. And then for measuring non-electrical phenomena, transducers are available. Transducers change one kind of energy into another. Speakers and microphones are two examples; the first changes electrical energy to sound waves and the second converts sound into electricity. Other typical transducers can transform mechanical stress, pressure, light, or heat into electrical signals. You can see that given the proper transducer, your test and measurement capabilities are almost endless with an oscilloscope.

Making measurements is easier if you understand the basics of how a scope works. You can think of the instrument in terms of the functional blocks illustrated in Figure 1: *vertical system, trigger system, horizontal system,* and *display system.*

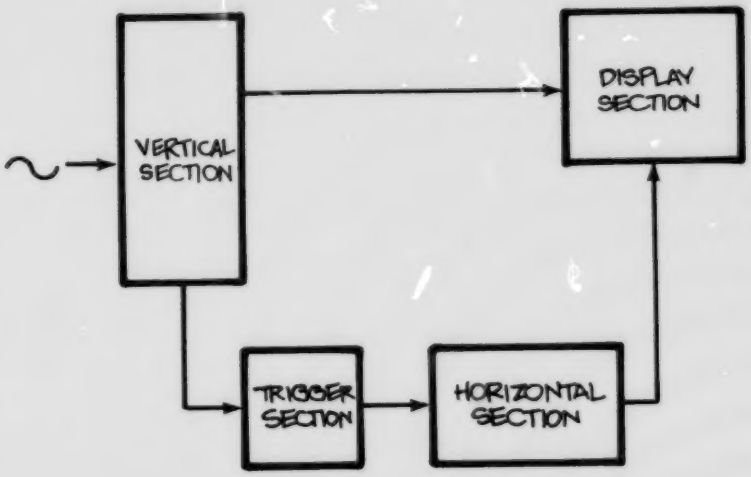


Figure 1.
THE BASIC OSCILLOSCOPE in its most general form has only four functional blocks: vertical, horizontal, trigger, and display systems (and sometimes, sections). The display system is also sometimes called the *CRT* (for cathode-ray tube) *section.*

Each is named for its function. The vertical system controls the vertical axis of the graph; anytime the electron beam that draws the graph moves up or down, it does so under control of the vertical system. The horizontal system controls the left to right movement of the beam. The trigger system determines when the oscilloscope draws; it *triggers* the beginning of the horizontal sweep across the screen. And the display system contains the cathode-ray tube, where the graph is drawn.

This part of the primer is divided into chapters for each of those functional blocks. The controls for each block are named first, and you can use a two-page, fold-out illustration of a Tektronix 2213 front panel at the back of the primer to locate them on your scope. Next the controls and their functions are described, and at the end of each chapter there are hands-on exercises using those controls.

The last chapter in this section describes probes. When you finish reading these five chapters, you'll be ready to make fast and accurate oscilloscope measurements.

But before you turn on your scope, remember that you should always be careful when you work with electrical equipment. Observe *all* safety precautions in your test and measurement operations. Always plug the power cord of the scope into a properly-wired receptacle before connecting your probes or turning on the scope; use the proper power cord for your scope, and use only the correct fuse. Don't remove the covers and panels of your scope.

Now fold out the front panel illustration at the back of the primer, so that it is visible as you read. Use the foldout and follow Exercise 1 to *initialize* (set in standard positions) the scope controls. These standard settings are necessary so that as you follow the directions on these pages, you'll see the same thing on your scope's CRT as is pictured or described he

Exercise 1. INITIALIZING THE SCOPE

Use the foldout figure and callouts to locate the controls mentioned here.

***1.** DISPLAY SYSTEM CONTROLS: Set the AUTO INTENSITY control at midrange (about halfway from either stop). Turn the AUTO FOCUS knob completely clockwise.*

***2.** VERTICAL SYSTEM CONTROLS: Turn the channel 1 POSITION control completely counterclockwise. Make sure the lefthand VERTICAL MODE switch is set to CH 1. Move both channel VOLTS/DIV switches to the least sensitive setting by rotating them completely counterclockwise. And make sure the center, red CAL controls are locked in their detents at the extreme clockwise position. Input coupling switches should be set to GND.*

***3.** HORIZONTAL SYSTEM CONTROLS: Make sure the HORIZONTAL MODE switch is set to NO DLY for no delay. (If you're using a 2215, move the switch to the A sweep position.) Rotate the SEC/DIV switch to 0.5 millisecond (0.5 ms). Make sure the red CAL (variable) switch in the center of the knob is in its detent position by moving it completely clockwise. And push in on the CAL switch to make sure the scope is not in a magnified mode.*

***4.** TRIGGER SYSTEM CONTROLS: Make sure the CAL HOLDOFF control is set to its full counterclockwise position. Set the trigger MODE switch (2215: A TRIGGER MODE) on AUTO. And move the trigger SOURCE switch (A SOURCE on a 2215) to INT (internal) and the INT selection switch (A&B INT on a 2215) to CH 1.*

After following the steps in Exercise 1, you should plug your scope into a properly-grounded outlet and turn it on. With a Tektronix 2200 scope, there's no need to change the scope's power supply settings to match the local power line; the scopes operate on main power from 90 to 250 Vac at 48 to 62 Hz.

CHAPTER 1. THE DISPLAY SYSTEM

The oscilloscope draws a graph by moving an electron beam across a phosphor coating on the inside of the CRT (cathode-ray tube). The result is a glow for a short time afterward tracing the path of the beam. A grid of lines etched on the inside of the faceplate serves as the reference for your measurements; this is the *graticule* shown in Figure 2.

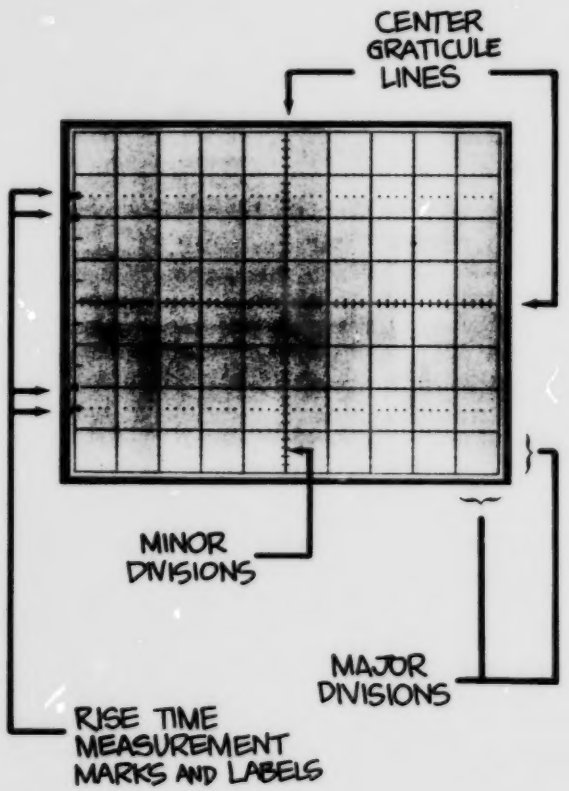


Figure 2.
THE GRATICULE is a grid of lines typically etched or silk-screened on the inside of the CRT faceplate. Putting the graticule inside — on the same plane as the trace drawn by the electron beam — and not on the outside of the glass — eliminates measurement inaccuracies called *parallax errors*. Parallax errors occur when the trace and the graticule are on different planes and the observer is shifted slightly from the direct line of sight. Though different sized CRT's may be used, graticules are usually laid out in an 8 x 10 pattern. Each of the eight vertical and ten horizontal lines block off *major divisions* (or just *divisions*) of the screen. The labeling on scope controls always refers to major divisions. The tick marks on the center graticule lines represent *minor divisions* or *subdivisions*. Since rise time measurements are very common, 2200 Series scope graticules include rise time measurement markings: dashed lines for 0 and 100% points, and labeled graticule lines for 10 and 90%.

Common controls for display systems include intensity and focus; less often, you will also find beam finder and trace rotation controls. On a Tektronix 2200 Series instrument they are all present, grouped next to and on the right of the CRT. At the top of the group is the intensity control (labeled AUTO INTENSITY on a 2200 because these instruments automatically maintain the trace intensity once it is set). The TRACE ROTATION adjustment is under that, and then the beam finder (BEAM FIND). Under the probe adjustment jack is the focus control (labeled AUTO FOCUS because it's also automatic). The functions of these controls are described below and their positions on the Tektronix 2213 Portable Oscilloscope are illustrated by the fold-out illustration at the rear of the booklet.

Beam Finder
The beam finder is a convenience control that allows you to locate the electron beam anytime it's off-screen. When you push the BEAM FIND button, you reduce the vertical and horizontal deflection voltages (more about deflection voltages later) and over-ride the intensity control so that the beam always appears within the 8 x 10-centimeter screen. When you see which quadrant of the screen the beam appears in, you'll know which directions to turn the horizontal and vertical POSITION controls to reposition the trace on the screen for normal operations.

Intensity
An intensity control adjusts the brightness of the trace. It's necessary because you use a scope in different ambient light conditions and with many kinds of signals. For instance, on square waves you might want to change the trace brightness to look at different parts of the waveform because the slower horizontal components will always appear brighter than the faster vertical components.

Intensity controls are also useful because the intensity of a trace is a function of both how bright the beam is and how long it's on-screen. As you select different sweep speeds (a *sweep* is one movement of the electron beam across the scope screen with the SEC/DIV switch, the beam ON and OFF times change and the beam has more or less time to excite the phosphor.

On most scopes, you have to turn the intensity up or down to restore the initial brightness. On the 2200 Series scopes, however, the automatic intensity circuit compensates for changes in sweep speed from 0.5 milliseconds (0.5 ms) to 0.5 microseconds (0.5 μs). Within this range, the automatic circuit maintains the same trace intensity you initially set with the AUTO INTENSITY control.

Focus
The scope's electron beam is focused on the CRT faceplate by an electrical grid within the tube. The focus control adjusts that grid for optimum trace focus. On a 2200 scope, the AUTO FOCUS circuit maintains your focus settings over most intensity settings (0.5 ms to 0.5 μs).

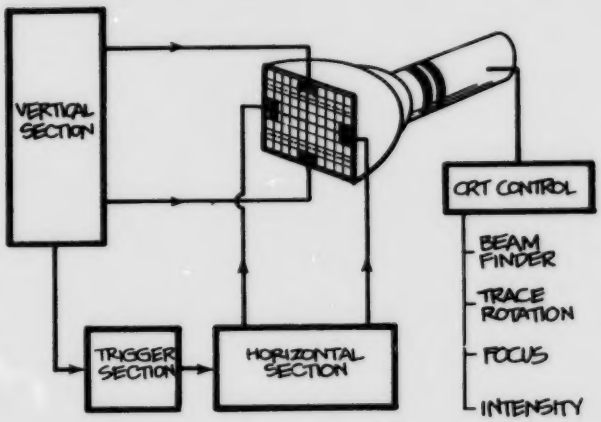
Trace Rotation

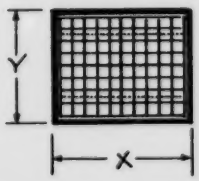
Another display control you'll find on the front panel of a 2200 Series instrument is TRACE ROTATION. The trace rotation adjustment allows you to electrically align the horizontal deflection of the trace with the fixed graticule. To avoid accidental misalignments when the scope is in use, the control is recessed and must be adjusted with a small screwdriver.

If this seems like a calibration item that should be adjusted once and then forgotten, you're right; that's true for most oscilloscope applications. But the earth's magnetic field affects the trace alignment and when a scope is used in many different positions — as a service scope may be — it's very handy to have a front panel trace rotation adjustment.

Using the Display Controls

The display system and its controls are shown as functional blocks in Figure 3. Use Exercise 2 to review the display controls.





THE Z-AXIS OF A CRT DETERMINES THE BRIGHTNESS OF THE ELECTRON BEAM AND WHETHER IT IS ON OR OFF.

Figure 3.
THE DISPLAY SYSTEM of your scope consists of the cathode-ray tube and its controls. To draw the graph of your measurements, the vertical system of the scope supplies the Y, or vertical, coordinates and the horizontal system supplies the X coordinates. There is also a Z dimension in a scope; it determines whether or not the electron beam is turned on, and how bright it is when it's on.

Exercise 2. THE DISPLAY SYSTEM CONTROLS

In Exercise 1 you initialized your scope and turned on the power. Now you can find the display system controls labeled on the foldout front panel illustration and use them as you follow these instructions.

1. *BEAM FIND: Locate the position of the electron beam by pushing and holding in the BEAM FIND button; then use the channel 1 vertical POSITION knob to position the trace on the center horizontal graticule line. Keep BEAM FIND depressed and use the horizontal POSITION control to center the trace. Release the beam finder.*

2. *AUTO FOCUS: The trace you have on the screen now should be out of focus. Make it as sharp as possible with the AUTO FOCUS control.*

3. *AUTO INTENSITY: Set the brightness at a level you like.*

4. *Vertical POSITION: Now you can use the vertical POSITION control to line up the trace with the first major division line above the center of the graticule.*

5. *TRACE ROTATION: Use a small screwdriver and the TRACE ROTATION control to rotate the trace in both directions. When you finish, align the trace parallel to the horizontal division line closest to it. (After setting the trace rotation, you may have to use the vertical POSITION control again to align the trace on the graticule line.)*

You have used all the scope's display system controls. If at the end of one of these chapters you're not going to go on immediately, be sure to turn your scope off.

CHAPTER 2. THE VERTICAL SYSTEM

The vertical system of your scope supplies the display system with the Y axis — or vertical — information for the graph on the CRT screen. To do this, the vertical system takes the input signals and develops *deflection voltages*. The display system then uses the deflection voltages to control — deflect — the electron beam.

The vertical system also gives you a choice of how you connect the input signals (called *coupling* and described below). And the vertical system provides internal signals for the trigger circuit (described in Chapter 4). Figure 4 illustrates the vertical system schematically.

Some of the vertical system controls — see the foldout front panel illustration for their locations — are: vertical position, sensitivity, and input coupling. Because all 2200s are two-channel scopes, you will have one set of these switches for each channel. There are also two switches for choosing the scope's vertical display mode and one control that allows you to invert the polarity of the channel 2 signal.

For the exercises in this chapter, you'll need a 10X probe like the Tektronix P6120 10X Probes supplied with every 2200 Series scope.

Vertical Position

Your scope's POSITION controls let you place the trace exactly where you want it on the screen. The two vertical POSITION controls (there's one for each channel) change the vertical placement of the traces from each vertical channel; the horizontal POSITION control changes the horizontal position of both channels at once.

Input Coupling

The input coupling switch for each vertical channel lets you control how the input signal is *coupled* to the vertical channel. DC (the abbreviation normally stands for *direct current)* input coupling lets you see all of an input signal. AC *(alternating current)* coupling blocks the constant signal components and permits only the alternating components of the input signal to reach the channel. An illustration of the differences is shown in Figure 5.

The middle position of the coupling switches is marked GND for ground. Choosing this position disconnects the input signal from the vertical system and makes a triggered display show the scope's chassis ground. The position of the trace on the screen in this mode is the ground reference level. Switching from AC or DC to GND and back is a handy way to measure signal voltage levels with respect to chassis ground. (Using the GND position does not ground the signal in the circuit you're probing.)

Vertical Sensitivity

A volts/division rotary switch controls the sensitivity of each vertical channel. Having different sensitivities extends the range of the scope's applications; with a VOLTS/DIV switch, a multipurpose scope is capable of accurately displaying signal levels from millivolts to many volts.

Using the volts/division switch to change sensitivity also changes the *scale factor,* the value of each major division on the screen. Each setting of the control knob is marked with a number that represents the scale factor for that channel. For example, with a setting of 10 V,

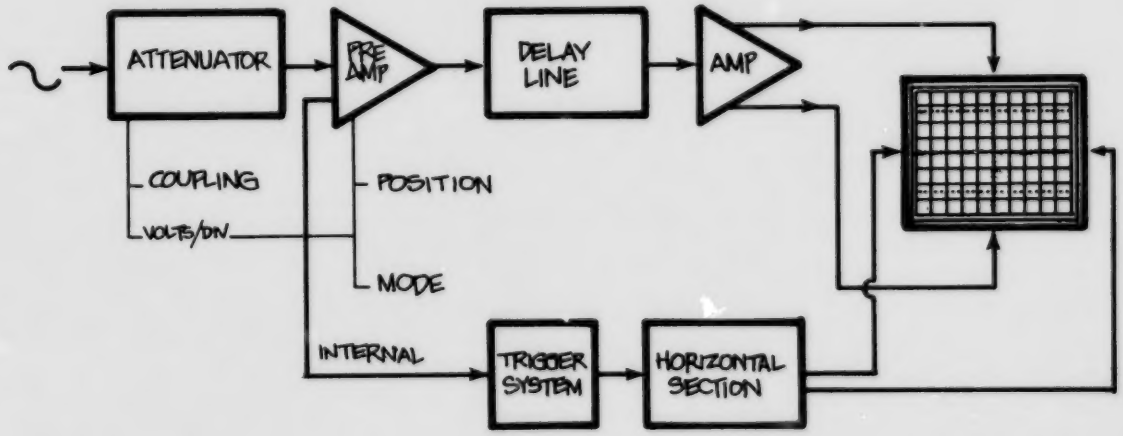


Figure 4.
THE VERTICAL SYSTEM of a Tektronix 2200 Series scope consists of two identical channels though only one is shown in the drawing. Each channel has circuits to couple an input signal to that channel, attenuate (reduce) the input signal when necessary, preamplify it, delay it, and finally amplify the signal for use by the display system. The delay line lets you see the beginning of a waveform even when the scope is triggering on it.

each of the eight vertical major divisions represents 10 volts and the entire screen can show 80 volts from bottom to top. With a VOLTS/DIV setting of 2 millivolts, the screen can display 16 mV from top to bottom.

If you pronounce the "/" in VOLTS/DIV as "per" when you read the setting, then you'll remember the setting is a scale factor; for example, read a 20 mV setting as "20 millivolts per division."

The probe you use influences the scale factor. Note that there are two unshaded areas under the skirts of the VOLTS/DIV switches. The right-hand area shows the scale factor when you use the standard 10X probe. The left area shows the factor for a 1X probe.

Variable VOLTS/DIV

The red CAL control in the center of the VOLTS/DIV switch provides a continuously variable change in the scale factor to a maximum greater than 2.5 times the VOLTS/DIV setting.

A variable sensitivity control is useful when you want to make quick amplitude comparisons on a series of signals. You could, for example, take a known signal of almost any amplitude and use the CAL control to make sure the waveform fits exactly on major division graticule lines. Then as you used the same vertical channel to look at other signals, you could quickly see whether or not the later signals had the same amplitude.

Channel 2 Inversion

To make differential measurements (described in Part II), you have to invert the polarity of one of your input channels. The INVERT control on the vertical amplifier for channel 2 provides this facility. When you push it in, the signal on channel 2 is inverted. When the switch is out, both channels have the same polarity.

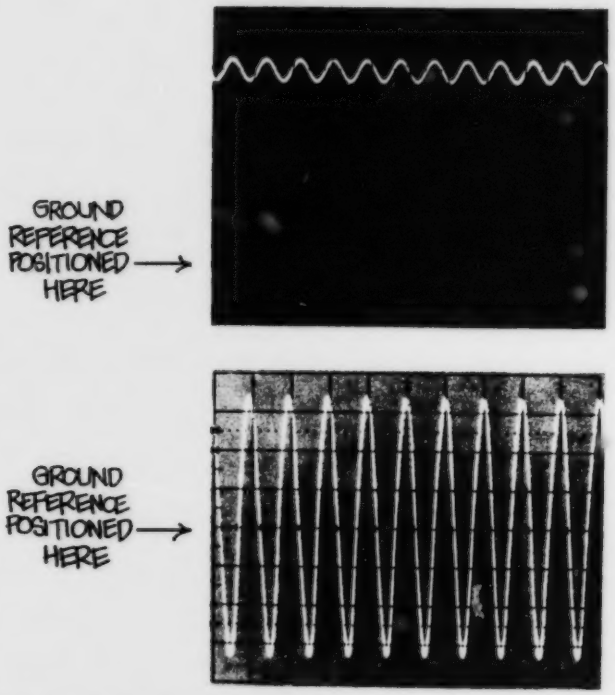


Figure 5.
VERTICAL CHANNEL INPUT COUPLING CONTROLS let you choose AC and DC input coupling and ground. DC coupling connects the entire input signal to the vertical channel. AC coupling blocks constant signal components and only connects alternating components to the vertical channel. The GND position disconnects the input signal and shows you the scope's chassis ground level. AC coupling is handy when the entire signal (alternating plus constant components) might be too large for the VOLTS/DIV switch settings you want. In a case like this, you might see something like the first photo. But eliminating the direct component allows you to look at the alternating signal with a VOLTS/DIV setting that is more convenient as in the second photo.

Vertical Operating Modes

Scopes are more useful if they have more than one vertical display mode, and with your Tektronix 2200, you have several controlled by two VERTICAL MODE switches: channel 1 alone; channel 2 alone; both channels in either the alternate or chopped mode; and both channels algebraically summed.

To make the scope display only channel 1, use the CH 1 position on the left-hand switch.

To display only channel 2, use the CH 2 position on the left-hand switch.

To see both channels in the alternate vertical mode, move the left-hand switch to BOTH (which enables the right-hand switch) and then move the right-hand switch to ALT. Now you can see both channels since the signals are drawn alternately. The scope completes a sweep on channel 1, then a sweep on channel 2, and so on.

To display both channels in the chop mode, you move the left-hand switch to BOTH and the right-hand one to CHOP. In the chop mode, the scope draws small parts of both signals by switching back and forth at a fast fixed rate while your eyes fill in the gaps.

Both chop and alternate are provided so that you can look at two signals at any sweep speed. The alternate mode draws first one trace and then the other, but not both at the same time. This works great at the faster sweep speeds when your eyes can't see the alternating. To see two signals at the slower sweeps, you need the chop mode.

If you want to see the two input signals combined into one waveform on the screen, use BOTH on the left-hand and ADD on the right-hand switch. This gives you an algebraically-combined signal: either channel 1 and 2 added, (CH 1) + (CH 2); or channel 1 minus channel 2 when channel 2 is inverted, (+CH 1) + (−CH 2).

Alternate Sweep Separation
On the 2215 dual time base scope, there is also a sweep separation control: A/B SWP SEP. It's used to change the position of the scope's B sweep traces with respect to the A sweeps. Using the A/B sweep separation in conjunction with the vertical POSITION controls lets you place all four traces (two channels and two time bases) on the screen so that they don't overlap. (Dual time base scope measurements are described in Chapter 9.)

Figure 6.
THE TEKTRONIX P6120 10X PROBE connects to the BNC connector of either channel 1 (shown) or 2; unlike the photo, the probe's ground strap is usually connected to the ground of the circuit you are working on. The probe adjustment jack is labeled PROBE ADJUST and is located near the CRT controls on the front panel.

Using the Vertical Controls
Before using the vertical system controls, make sure all the controls are positioned where you left them at the end of the last chapter:

- AUTO INTENSITY and AUTO FOCUS set for a bright, crisp trace;
- trigger SOURCE (A SOURCE on the 2215) switch on INT and the INT (2215: A&B INT) switch on CH 1;
- trigger MODE (2215: A TRIGGER MODE) switch on AUTO;
- trigger VAR HOLDOFF control in its extreme counterclockwise position;
- SEC/DIV (2215: A and B SEC/DIV) switch to 0.5 ms;
- both channel VOLTS/DIV switches on 100 V (10X probe reading);
- both CAL VOLTS/DIV switches in their detents at the extreme clockwise position;
- input coupling levers in GND;
- VERTICAL MODE is CH 1;
- and HORIZONTAL MODE is NO DLY (2215 mode is A).

Now connect your 10X probe on the channel 1 BNC connector on the front panel of your scope. (BNC means "bayonet Neill-Concelman"; named for Paul Neill, who developed the N Series connector at Bell Labs, and Carl Concelman, who developed the C Series connector.)

Put the tip of the probe into the PROBE ADJ jack. Probes come with an alligator-clip ground strap that's used to ground the probe to the circuit-under-test. Clip the ground lead onto the collar of the channel 2 BNC connector as shown in Figure 6

Use the callouts on the foldout figure to remind yourself of the control locations and follow the directions in Exercises 3 to review the vertical system controls.

Exercise 3. VERTICAL SYSTEM CONTROLS

Compensating Your Probe

1. Turn on the scope and move the CH 1 VOLTS/DIV switch clockwise to 0.5 V; remember the P6120 is a 10X probe, so use the VOLTS/DIV readout to the right.

2. Switch the channel 1 input coupling to AC.

3. If the signal on the screen isn't steady, turn the trigger LEVEL (A TRIGGER LEVEL on the 2215) control until the signal stops moving and the TRIG'D light is on. (Use the AUTO FOCUS control if you think you can get the signal sharper, and AUTO INTENSITY to adjust the brightness.)

4. Next, compensate your probe. There's a screwdriver adjustment on the compensation box at the base of the probe; turn it until the tops and bottoms of the square wave on the screen are flat. (There's more information about probes and compensation in Chapter 5.)

Controlling Vertical Sensitivity

1. The probe adjustment signal is a square wave of approximately 0.5 volts, and the scale factor for channel 1 is now a half-volt per division. At this setting every major division on the screen represents half a volt. Use the channel 1 vertical POSITION control to line up the bottom edge of the waveform with the center graticule line. The tops of the square wave should be just touching the next major division line, proving the probe adjustment signal is approximately 0.5 volts. (Note that the probe adjustment signal is not a critical circuit in the scope; this is why the square wave is approximately 0.5 volts.)

2. Turn the VOLTS/DIV switch two more click stops to the right. The channel 1 scale factor is now 0.1 volts/division, and the signal – still half a volt – is now about five major divisions in amplitude.

3. Turn the CAL VOLTS/DIV control to the left. That will take it out of its calibrated detent position and let you see its effect. Since it reduces the scale factor ≥2½ times, the signal should be less than two major divisions in amplitude with this control all the way to the left. If it isn't exactly that, don't worry. The variable volts/division controls are used to compare signals, not make amplitude measurements, and consequently the exact range of variation isn't critical. Return the variable control to its detent.

Coupling The Signal

1. Switch your channel 1 input coupling to GND and position the trace on the center graticule. Switch back to the AC coupling position. Note that the waveform is centered on the screen. Move the CH 1 VOLTS/DIV switch back to 0.5 volts and note that the waveform is still centered around the zero reference line.

2. Switch to DC coupling. The top of the probe adjustment signal should be on the center graticule line and the signal should reach to the next lower major division. Now you can see the difference between AC and DC coupling. AC coupling blocked the constant part of the signal and just showed you a half-volt, peak-to-peak, square wave centered on the zero reference you set at the center of the screen. But the DC coupling showed you that the constant component of the square wave was all negative-going with respect to ground, because in DC, all signal components are connected to the vertical channel.

The Vertical Mode Controls

1. So far you've been using your scope to see what channel 1 can tell you, but that's only one of many possible vertical modes. Look at the trace for channel 2 by moving the scope's left-most VERTICAL MODE switch to CH 2. The input coupling for channel 2 should still be GND at this point, so what you'll see is the ground reference line. Line up this trace with the graticule line second from the top of the screen with the channel 2 POSITION control.

2. Now move the lever on the left-hand vertical mode switch to BOTH. That lets you pick one of the vertical modes controlled by the right-hand side vertical mode switch; move it to ALT. You've just selected the alternate vertical mode. In this mode, your scope alternates between the signals on channel 1 and 2, drawing one complete sweep on channel 1 first, and then drawing a complete sweep on channel 2. You can see this happening when you slow down the sweep speed, so move the SEC/DIV swtich left to 0.1 seconds per division. Now you can see the two dots from the AC-coupled channel 1 move across the screen for one sweep. Then the single dot from channel 2 will move across the screen. The point is that in the alternate mode each channel is drawn completely before the scope switches to the other channel.

3. Turn the SEC/DIV switch back to 0.5 ms and switch to CHOP as your vertical mode. The display looks a lot like the alternate mode, but the way it's achieved is entirely different. In alternate, you saw that one channel's signal was completely written before the other started. When you're looking at slow signals with your scope, that can be a bother because only one trace at a time will be on-screen. In the chop mode, however, the scope switches back and forth very quickly between the two traces so that a little part of each is drawn before going on to the next. When you look at the screen, both signals seem continuous because the scope is "chopping" back and forth at a very fast rate – approximately 250 kHz in the 2200 Series. You can see the chopping if you pick a very fast sweep speed. Move the SEC/DIV switch to 10 µs. Now the display shows broken lines because of the chopping. CHOP is most useful for slow sweep speeds, and ALT for faster sweeps.

4. Move the SEC/DIV switch back to 0.5 ms. There's one more vertical mode: ADD. In the add mode, the two signals are algebraically summed (either CH 1 + CH 2, or CH 1 − CH 2 when channel 2 is inverted). To see it in operation, move the right-hand VERTICAL MODE switch to ADD. Now you can see the combined signal roughly halfway between where the two separate signals were.

CHAPTER 3. THE HORIZONTAL SYSTEM

To draw a graph, your scope needs horizontal as well as vertical data. The horizontal system of your scope supplies the second dimension by providing the deflection voltages to move the electron beam horizontally. And the horizontal system contains a *sweep generator* which produces a sawtooth waveform, or *ramp* (see Figure 7), that is used to control the scope's sweep rates.

It's the sweep generator that makes the unique functions of the modern oscilloscope possible. The circuit that made the rate of rise in the ramp linear — a refinement pioneered by Tektronix — was one of the most important advances in oscillography. It meant that the horizontal beam movement could be calibrated directly in units of time. That advance made it possible for you to measure time between events much more accurately on the scope screen.

Because it is calibrated in time, the sweep generator is often called the *time base*. It lets you pick the time units, observing the signal for either very short times measured in nanoseconds or microseconds, or relatively long times of several seconds.

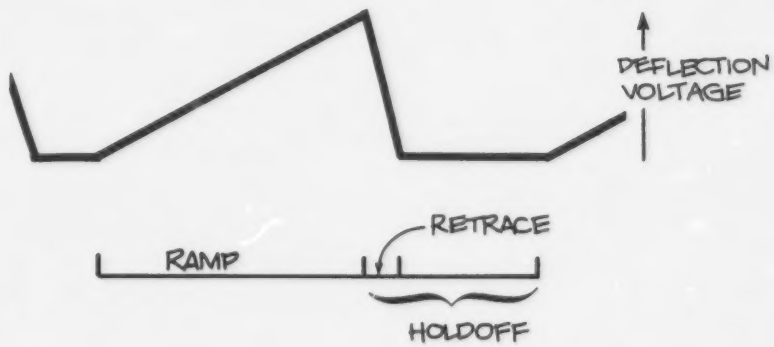


Figure 7.
THE SAWTOOTH WAVEFORM is a voltage ramp produced by the sweep generator. The rising portion of the waveform is called the *ramp*, the falling edge is the *retrace*, and the time between ramps is the *holdoff* time. The sweep of the electron beam across the screen of a scope is controlled by the ramp and the return of the beam to the left side of the screen takes place during the retrace.

The horizontal system controls of a Tektronix 2213 scope are shown in the foldout figure: the horizontal POSITION control is near the top of the panel, and the HORIZONTAL MODE control is below it; the magnification and variable sweep speed control is a red knob in the center of the SEC/DIV switch; at the bottom of the column of horizontal system controls are the DELAY TIME switch and the delay time MULTIPLIER. The dual time base 2215 has two concentric SEC/DIV controls, and a B DELAY TIME POSITION control instead of the delay time switch and multiplier. (The scope controls that you use to position the start of a delayed sweep are also often called *delay time multipliers* or DTMs.)

Horizontal Position

Like the vertical POSITION controls, you use the horizontal POSITION control to change the location of the waveforms on the screen.

Horizontal Operating Modes

Single time base scopes usually have only one horizontal operating mode, but the 2213 offers normal, intensified, or delayed-sweep operating modes. Dual time base scopes like the 2215 usually let you select either of two sweeps. The A sweep is undelayed (like the sweep of a single time base instrument), while the B sweep is started after a delay time. Additionally, some scopes with two time bases — and the 2215 is an example again — let you see the two sweeps at once: the A sweep intensified by the B sweep; and the B sweep itself. This is called an *alternate horizontal operating mode*.

Only the normal horizontal operating mode is used in these first few chapters, so leave your scope's HORIZONTAL OPERATING MODE switch in NO DLY (no delay) on the 2213 and A (for A sweep only) on the 2215. Chapter 9, in the second section of this primer, describes how to make delayed sweep measurements.

Sweep Speeds

The seconds/division switch lets you select the rate at which the beam sweeps across the screen; changing SEC/DIV switch settings allows you to look at longer or shorter time intervals of the input signal. Like the vertical system VOLTS/DIV switch, the control's markings refer to the screen's scale factors. If the SEC/DIV setting is 1 ms, that means that each horizontal major division represents 1 ms and the total screen will show you 10 ms.

On the 2215, which has two time bases, there are two SEC/DIV controls. The A sweep offers all the settings described below; the SEC/DIV switch for the delayed B sweep has settings for 0.05 μs/div to 50 ms/div.

All the instruments of the Tektronix 2200 Series offer sweep speeds from a half-second for each division to 0.05 μs/division. The markings appearing on the scopes are:

.5 s	half a second
2 s	0.2 second
1 s	0.1 second
50 ms	50 milliseconds (0.05 second)
20 ms	20 milliseconds (0.02 second)
10 ms	10 milliseconds (0.01 second)
5 ms	5 milliseconds (0.005 second)
2 ms	2 milliseconds (0.002 second)
1 ms	1 millisecond (0.001 second)
.5 ms	half a millisecond (0.0005 second)
.2 ms	0.2 millisecond (0.0002 second)
.1 ms	0.1 millisecond (0.0001 second)
50 μs	50 microseconds (0.00005 second)
20 μs	20 microseconds (0.00002 second)
10 μs	10 microseconds (0.00001 second)
5 μs	5 microseconds (0.000005 second)
2 μs	2 microseconds (0.000002 second)
1 μs	1 microsecond (0.000001 second)
.5 μs	half a microsecond (0.0000005 second)
.2 μs	0.2 microsecond (0.0000002 second)
.1 μs	0.1 microsecond (0.0000001 second)
.05 μs	0.05 microseconds (0.00000005 second)

Scopes also have an XY setting on the SEC/DIV switch for making the X-Y measurements described in Chapter 9.

Variable SEC/DIV
Besides the calibrated speeds, you can change any sweep speed by turning the red CAL control in the center of the SEC/DIV switch counterclockwise. This control slows the sweep speed by at least 2.5:1, making the slowest sweep you have 0.5 seconds x 2.5, or 1.25 seconds/division. Remember that the detent in the extreme clockwise direction is the calibrated position.

Horizontal Magnification
Most scopes offer some means of horizontally magnifying the waveforms on the screen. The effect of magnification is to multiply the sweep speed by the amount of magnification. On 2200 Series scopes there is a 10X horizontal magnification that you engage by pulling out on the red CAL switch. The 10X horizontal magnification gives you a sweep speed ten times faster than the SEC/DIV switch setting; for example, 0.05 μs/division magnified is a very fast 5-nanosecond/division sweep.

The 10X magnification is useful when you want to look at signals and see details that occur very closely together in time.

The DELAY TIME and MULTIPLIER Controls
This switch and dial are used in conjunction with either the intensified or delayed-sweep horizontal operating modes in the 2213. These features are described later under "Delayed Sweep Measurement" in Chapter 9.

The B DELAY TIME POSITION Control
This calibrated 10-turn dial is used to position the beginning of the B sweep relative to the A sweep in a 2215. Its uses are described under "Delayed Sweep Measurements" in Chapter 9.

Using the Horizontal Controls
As you can see in Figure 8, the horizontal system can be divided into two functional blocks: the horizontal amplifier and the sweep generator.

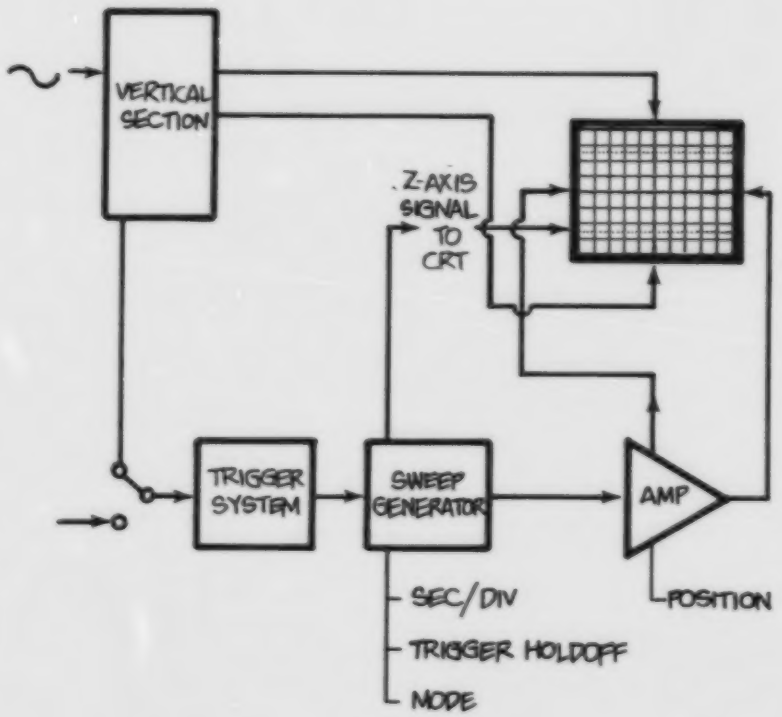


Figure 8.
HORIZONTAL SYSTEM components include the sweep generator and the horizontal amplifier. The sweep generator produces a sawtooth waveform that is processed by the amplifier and applied to the horizontal deflection plates of the CRT. The horizontal system also provides the Z axis of the scope; the Z axis determines whether or not the electron beam is turned on — and how bright it is when it's on.

THE HORIZONTAL SYSTEM CONT.

To familiarize yourself with the horizontal system controls, follow the directions in Exercise 4 and refer to the foldout for control locations. First, make sure the front panel controls have these settings:

- the SEC/DIV switch is on 0.5 ms;
- the trigger SOURCE (A TRIGGER SOURCE on the 2215) is INT; INT (2215: A&B INT) is on CH 1;
- the trigger MODE (2215: A TRIGGER MODE) is AUTO;
- the channel 2 INVERT switch is out (no signal inverting);
- and HORIZONTAL MODE is NO DLY (A on the 2215)

Exercise 4. THE HORIZONTAL SYSTEM CONTROLS

1. Switch the VERTICAL MODE to CH 1 and the CH 1 VOLTS/DIV setting to 0.5 volt. Be sure your probe is connected to channel 1 and the PROBE ADJ jack. Turn on your scope and move the channel 1 input coupling lever to GND and center the signal on the screen with the POSITION control. Switch to AC coupling.
2. Now you can use the horizontal system of your scope to look at the probe adjustment signal. Move the waveform with the horizontal POSITION control until one rising edge of the waveform is lined up with the center vertical graticule. Examine the screen to see where the leading edge of the next pulse crosses the horizontal center line of the graticule. Count major and minor graticule markings along the center horizontal graticule and remember the number.
3. Change sweeps to 0.2 ms, line up a rising edge with the vertical graticule on the left edge of the screen and count to the next rising edge. Because the switch was changed from 0.5 to 0.2 ms, the waveform will look 2.5 times as long as before. Of course, the signal hasn't changed, only the scale factor.
4. In the middle of the SEC/DIV switch is the red variable control; in its counterclockwise detent, the settings of the SEC/DIV switch are calibrated. Move the control from its detent to see its effect on the sweep speed. Note that now the cycles of the waveform are approximately two-and-a-half times smaller. Return the CAL control to its detent.
5. Move the SEC/DIV switch to 0.5 ms and then pull out the red CAL control. This gives you a 10X magnification of the sweep speed. In other words, every setting on the SEC/DIV switch will result in a sweep that's ten times faster; for example, the sweep now is 0.05 ms/division, not 0.5 ms.
6. While your scope is magnifying the probe adjustment signal, use the horizontal POSITION control. Its range is now magnified as well, and the combination of magnified signal and POSITION control gives you the ability to examine small parts of a waveform in great detail. Return your scope to its normal sweep speed range by pushing the CAL switch in.

CHAPTER 4. THE TRIGGER SYSTEM

So far you've found that the display system draws the waveforms on the screen, the vertical system supplies the vertical information for the drawing, and the horizontal system provides the time axis. In other words, you know how the oscilloscope draws a graph; the only thing missing is the "when": when should the other circuits of your scope start drawing the signal, and when shouldn't they?

The when is the trigger and it's important for a number of reasons. First, because getting time-related information is one of the reasons you use a scope. Equally important is that each drawing start with the same "when."

Obviously the graph drawn on the screen isn't the same one all the time you're watching. If you're using the 0.05 μs SEC/DIV setting, the scope is drawing 1 graph every 0.5 μs (0.05 μs/division times ten screen divisions). That's 2,000,000 graphs every minute (not counting retrace and holdoff times, which we'll get to shortly). Imagine the jumble on the screen if each sweep started at a different place on the signal.

But each sweep does start at the right time — if you make the right trigger system control settings. Here's how it's done. You tell the trigger circuit which trigger signal to select with the source switches. With an external signal, you connect the trigger signal to the trigger system circuit with the external coupling controls. Next you set the trigger circuit to recognize a particular voltage level on the trigger signal with the slope and level controls. Then everytime that level occurs, the sweep generator is turned on. The process is diagrammed in Figure 9.

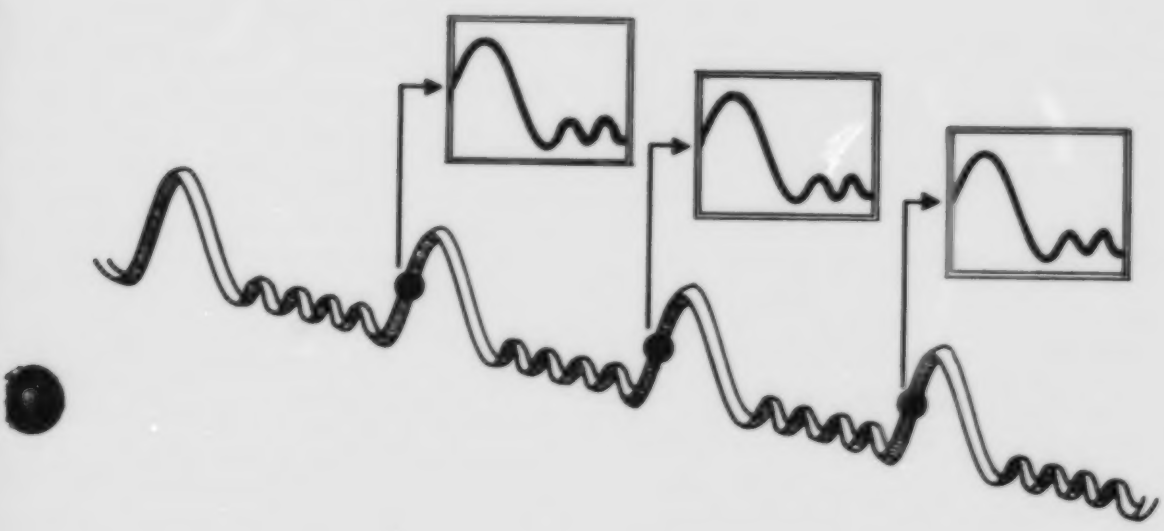


Figure 9.
TRIGGERING GIVES YOU A STABLE DISPLAY because the same trigger point starts the sweep each time. Slope and level controls define the trigger points on the trigger signal. When you look at a waveform on the screen, you're seeing all those sweeps overlaid into what appears to be one picture.

Instruments like those in the Tektronix 2200 Portable Oscilloscope family offer a variety of trigger controls. Besides those already mentioned, you also have controls that determine how the trigger system operates (trigger operating mode) and how long the scope waits between triggers (holdoff).

The control positions are illustrated by the foldout at the end of the primer. All are located on the far right of the front panel. On the 2213, the variable trigger holdoff (VAR HOLDOFF) is at the top, and immediately below it is the trigger MODE switch. Below that the trigger SLOPE and LEVEL controls are grouped. Then a set of three switches controls the trigger sources and the external trigger coupling. At the bottom of the column of trigger controls is the external trigger input BNC connector.

On dual time base 2215 scopes, there is a slightly different control panel layout because you can have a separate trigger for the B sweep.

Trigger Level and Slope

These controls define the trigger point. The SLOPE control determines whether the trigger point is found on the rising or the falling edge of a signal. The LEVEL control determines where on that edge the trigger point occurs. See Figure 10.

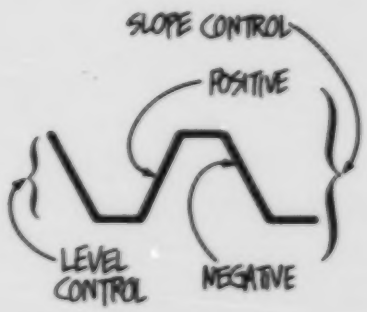


Figure 10.
SLOPE AND LEVEL CONTROLS determine where on the trigger signal the trigger actually occurs. The SLOPE control specifies either a positive (also called the *rising* or *positive-going)* edge or on a negative *(falling* or *negative-going)* edge. The LEVEL control allows you to pick where on the selected edge the trigger event will take place.

Variable Trigger Holdoff

Not every trigger event can be accepted as a trigger. The trigger system will not recognize a trigger during the sweep or the retrace, and for a short time afterward called the *holdoff period*. The retrace, as you remember from the last chapter, is the time it takes the electron beam to return to the left side of the screen to start another sweep. The holdoff period provides additional time beyond the retrace that is used to ensure that your display is stable, as illustrated by Figure 11.

Sometimes the normal holdoff period isn't long enough to ensure that you get a stable display; this possibility exists when the trigger signal is a complex waveform with many possible trigger points on it. Though the waveform is repetitive, a simple trigger might get you a series of patterns on the screen instead of the same pattern each time. Digital pulse trains are a good example; each pulse is very much like any other, so there are many possible trigger points, not all of which result in the same display.

What you need now is some way to control when a trigger point is accepted. The variable trigger holdoff control provides the capability. (The control is actually part of the horizontal system — because it adjusts the holdoff time of the sweep generator — but its function interacts with the trigger controls.) Figure 12 diagrams a situation where the variable holdoff is useful.

Trigger Sources

Trigger sources are grouped into two categories that depend on whether the trigger signal is provided internally or externally. The source makes no difference in how the trigger circuit operates, but internal triggering usually means your scope is triggering on the same signal that it is

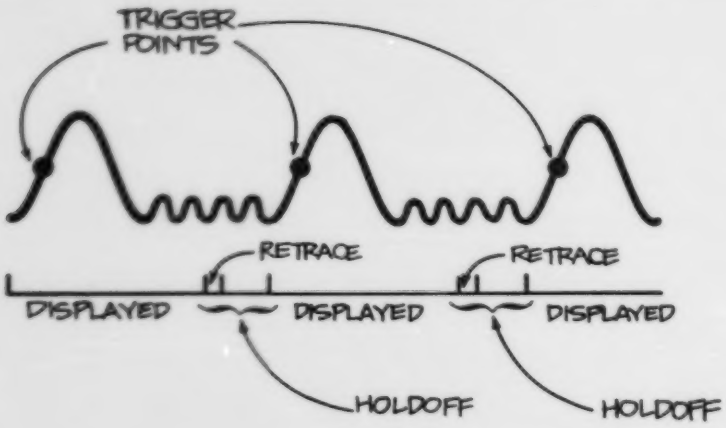


Figure 11.
TRIGGER HOLDOFF TIME ensures valid triggering. In the drawing only the labeled points start the display because no trigger can be recognized during the sweep or the retrace and holdoff period. The retrace and holdoff times are necessary because the electron beam must be returned to the left side of the screen after the sweep, and because the sweep generator needs reset time. The CRT Z axis is *blanked* between sweeps and *unblanked* during sweeps.

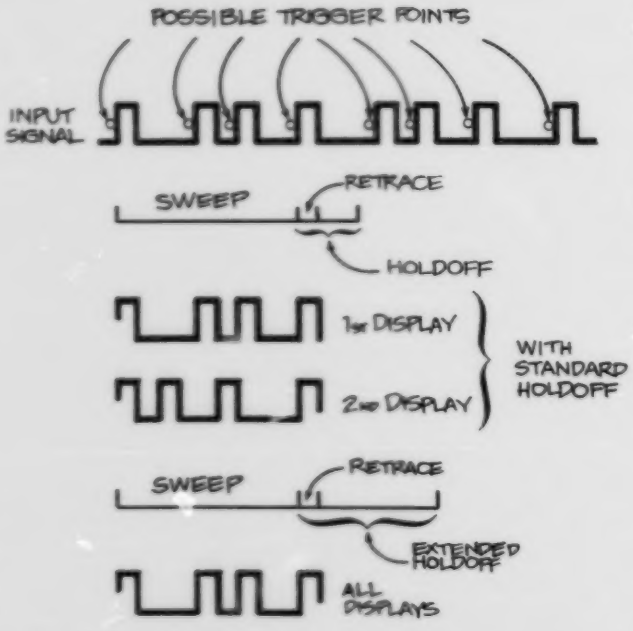


Figure 12.
THE VARIABLE HOLDOFF CONTROL lets you make the scope ignore some potential trigger points. In the example, all the possible trigger points in the input signal would result in an unstable display. Changing the holdoff time to make sure that the trigger point appears on the same pulse in each repetition of the input signal is the only way to ensure a stable waveform.

displaying. That has the obvious advantage of letting you see where you're triggering.

Two switches on the front panel (labeled SOURCE and INT) determine the trigger source. The internal triggering sources are enabled when you move the SOURCE lever to INT. In this position, you can trigger the scope on the signal from either channel, or you can switch to VERT MODE.

Triggering on one of the channels works just like it sounds: you've set the scope to trigger on some part of the waveform present on that channel.

Using the VERTICAL MODE setting on the internal source switch means that the scope's VERTICAL MODE switches determine what signal is used for triggering. If the VERTICAL MODE switches are set at CH 1, then the signal on channel 1 triggers the scope. If you're looking at channel 2, then that channel triggers it. If you switch to the alternate vertical mode, then the scope looks for triggers alternately on the two channels. If the vertical mode is ADD, then CH 1 + CH 2 is the triggering signal. And in the CHOP vertical mode, the scope triggers the same as in ADD, which prevents the instrument from triggering on the chop frequency instead of your signals.

You can see that vertical mode triggering is a kind of automatic source selection that you can use when you must switch back and forth between vertical modes to look at different signals.

But triggering on the displayed signal isn't always what you need, so external triggering is also available. It often gives you more control over the display. To use an external trigger, you set the SOURCE switch to its EXT position and connect the triggering signal to the BNC connector marked EXT INPUT on the front panel. Occasions when external triggering is useful often occur in digital design and repair; there you might want to look at a long train of very similar pulses while triggering with an external clock or with a signal from another part of the circuit.

The LINE position on the SOURCE switch gives you another triggering possibility: the power line. Line triggering is useful anytime you're looking at circuits that are dependent on the power line frequency. Examples include devices like light dimmers and power supplies.

These are all the trigger source possibilities on a 2200 Series scope:

	Switch Positions	
Trigger Source	SOURCE	INT
channel 1 only	INT	CH 1
channel 2 only	INT	CH 2
external	EXT	disabled
line	LINE	disabled
vertical mode (either channel 1 or 2 or both)	INT	VERT MODE

Trigger Operating Modes

The 2200 Series trigger circuits can operate in four modes: normal, automatic, television, and vertical mode.

One of the most useful is the normal trigger mode (marked NORM on the MODE switch) because it can handle a wider range of trigger signals than any other triggering mode. The normal mode does not permit a trace to be drawn on the screen if there's no trigger. The normal mode gives you the widest range of triggering signals: from DC to 60 MHz.

In the automatic (or "bright baseline") mode (labeled AUTO on the front panel): a trigger starts a sweep; the sweep ends and the holdoff period expires. At that point a timer begins to run; if another trigger isn't found before the timer runs out, a trigger is generated anyway causing the bright baseline to appear even when there is no waveform on the channel. In the 2200 Series, the automatic mode is a signal-seeking auto mode. This means that for most of the signals you'll be measuring, the auto mode will match the trigger level control to the trigger signal. That makes it most unlikely that you will set the trigger level control outside of the signal range. The auto mode lets you trigger on signals with changing voltage amplitudes or waveshapes without making an adjustment of the LEVEL control.

Another useful operating mode is television triggering. Most scopes with this mode let you trigger on tv fields at sweeps of 100 μs/division and slower, and tv lines at 50 μs/div or faster. With a 2200 Series scope, you can trigger on either fields or lines at any sweep speed; for tv field triggering, use the TV FIELD switch position, and for television line triggering, use the NORM or AUTO settings.

You'll probably use the normal and automatic modes the most often. The AUTO because it's essentially totally automatic, and normal because it's the most versatile. For example, it's possible to have a low frequency signal with a repetition rate that is mismatched to the run-out of an automatic mode timer; when that happens the signal will not be steady in the auto mode. Moreover, the automatic signal-seeking mode can't trigger on very low frequency trigger signals. The normal mode, however, will give you a steady signal at any rep rate.

The last 2200 Series trigger operating mode, the vertical mode, is unique in its advantages. Selecting the VERT MODE position on the INT switch automatically selects the trigger source as you read in "Trigger Source" above. It also makes alternate triggering possible. In this operating mode, the scope triggers alternately on the two vertical channels. That means you can look at two completely unrelated signals. Most scopes only trigger on one channel or the other when the two signals are not synchronous.

Here's a review of the 2200 trigger modes:

Trigger Operating Mode	Switch Settings
normal	NORM on the MODE switch
automatic	AUTO on the MODE switch
television field	TV FIELD on the MODE switch
television line	NORM or AUTO on the MODE switch
vertical mode	VERT MODE on the INT switch

THE TRIGGER SYSTEM CONT.

Triggering Coupling

Just as you may pick either alternating or direct coupling when you connect an input signal to your scope's vertical system, you can select the kind of coupling you need when you connect a trigger signal to the trigger system's circuits. For internal triggers, the vertical input coupling selects the trigger coupling. For external trigger signals, however, you must select the coupling you want:

Coupling	Applications
DC	DC couples all elements of the triggering signal (both AC and DC) to the trigger circuit.
DC with attenuation	If you want DC coupling and the external trigger is too large for the trigger system, move the TRIGGER COUPLING switch to its DC÷10 setting.
AC	This coupling blocks DC components of the trigger signal and couples only the AC components.

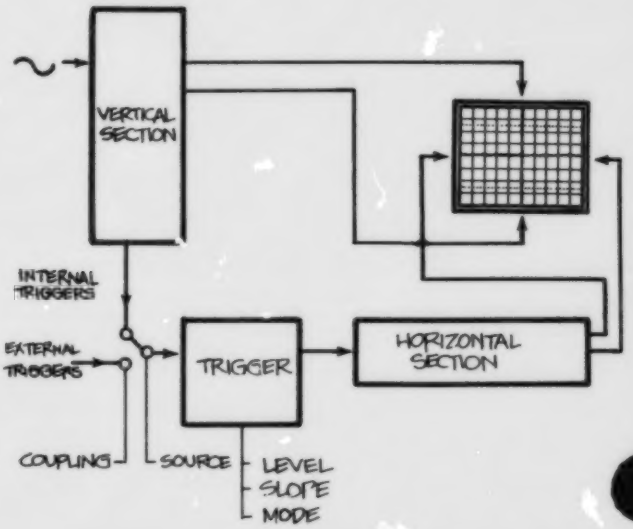


Figure 13.
THE TRIGGER CIRCUIT AND ITS CONTROLS are shown in the diagram above. Trigger source describes whether or not the trigger signal is internal or external to the scope. Coupling controls the connection of an external trigger to the trigger circuit. The level and slope controls determine where the trigger point will be on the trigger signal. And the mode control determines the operations of the trigger circuit.

Using the Trigger Controls

To review what you've learned about the trigger circuit and its controls (shown schematically in Figure 13), first make sure all your controls are in these positions:

- 0.5 VOLTS/DIV on channel 1 and CAL in its detent position;
- AC vertical coupling;
- CH 1 on the VERTICAL MODE switch;
- 0.5 ms sweep speed and no magnification or variable SEC/DIV;
- your trigger settings should be AUTO for MODE, INT for SOURCE, and CH 1 for INT

Turn your scope on with the probe connected to the channel 1 BNC connector and the probe adjustment jack. Use the foldout figure to remind yourself of the control locations and follow the directions in Exercise 5.

Exercise 5. TRIGGER CONTROLS

1. Move the trace to the right with the horizontal POSITION control until you can see the beginning of the signal (you'll probably have to increase the intensity to see the faster vertical part of the waveform). Watch the signal while you operate the SLOPE control. If you pick +, the signal on the screen starts with a rising edge; the other SLOPE control position makes the scope trigger on a falling edge.

2. Now move the LEVEL control back and forth through all its travel; you'll see the leading edge climb up and down the signal. The scope remains triggered because you are using the AUTO setting.

3. Turn the MODE switch to NORM. Now when you use the LEVEL control to move the trigger point, you'll find places where the scope is untriggered. This is an illustration of the essential difference between normal and automatic triggering.

4. You can also see the difference between the two triggering modes by using channel 2, even with that channel coupled to GND for ground. Change both the vertical display mode and the INT (2215: A&B INT) switches to CH 2. With NORM triggering, there's no signal; with AUTO, you'll see the baseline. Try it.

5. Without a trigger signal applied to the EXT INPUT BNC connector, it's impossible to show you the use of this trigger source, but the trigger MODE, SLOPE, and LEVEL controls will all operate the same for either internal or external triggers. One difference between internal and external sources, however, is the sensitivity of the trigger circuit. All external sources are measured in voltage (say, 150 millivolts) while the internal sources are rated in divisions. In other words, for internal signals, the displayed amplitude makes a difference. Now change the VERTICAL MODE and INT switches back to CH 1, and switch to the NORM mode. Use the LEVEL control and notice how much control range there is. Now change the CH 1 VOLTS/DIV switch to 0.1 V and use the LEVEL control. There's more control range now.

6. The alternate-channel triggering with vertical mode triggering can't be demonstrated without two unrelated signals on the channels, but you'll find it useful the first time such an occasion comes up. You can take another look at the difference between the normal and auto trigger operating modes. Move the LEVEL control slowly in the NORM mode until the scope is untriggered. Now switch the trigger operating mode to AUTO and note that the waveform is automatically triggered.

CHAPTER 5. ALL ABOUT PROBES

PART I

Connecting all the measurement test points you'll need to the inputs of your oscilloscope is best done with a probe like the one illustrated in Figure 14. Though you could connect the scope and circuit-under-test with just a wire, this simplest of all possible connections would not let you realize the full capacities of your scope. The connection would probably load the circuit and the wire would act as an antenna and pick up stray signals — 60 Hz power, CBers, radio and tv stations — and these would be displayed on the screen along with the signal of interest.

Circuit Loading

Using a probe instead of a bare wire minimizes stray signals, but there's still an effect from putting a probe in a circuit called *circuit loading*. Circuit loading modifies the environment of the signals in the circuit you want to measure; it changes the signals in the circuit-under-test, either a little or lot, depending on how great the loading is.

Circuit loading is resistive, capacitive, and inductive. For signal frequencies under 5 kHz, the most important component of loading is resistance. To avoid significant circuit loading here, all you need is a probe with a resistance at least two orders of magnitude greater than the circuit impedance (100 MΩ probes for 1 MΩ sources; 1 MΩ probes for 10 kΩ sources, and so on).

When you are making measurements on a circuit that contains high frequency signals, inductance and capacitance become important. You can't avoid adding capacitance when you make connections, but you can avoid adding more capacitance than necessary.

One way to do that is to use an attenuator probe; its design greatly reduces loading. Instead of loading the circuit with capacitance from the probe tip plus the cable plus the scope's own input, the 10X attenuator probe introduces about ten times less capacitance, as little as 10-14 picofarads (pF). The penalty is the reduction in signal amplitude from the 10:1 attenuation.

These probes are adjustable to compensate for variations in oscilloscope input capacitance and your scope has a reference signal available at the front panel. Making this adjustment is called *probe compensation* and you did it as the first step in Exercise 3 of Chapter 2.

Remember when you are measuring high frequencies, that the probe's impedance (resistance and reactance) changes with frequency. The probe's specification sheet or manual will contain a chart like that in Figure 15 that shows this change. Another point to remember when making high frequency measurements is to be sure to securely ground your probe with as short a ground clip as possible. As a matter of fact, in some very high frequency applications a special socket is provided in the circuit and the probe is plugged into that.

Measurement System Bandwidth

Then there is one more probe characteristic to consider: bandwidth. Like scopes, probes have bandwidth limitations; each has a specified range within which it does not attenuate the signal's amplitude more than −3 dB (0.707 of the original value). But don't assume that a 60 MHz probe and a 60 MHz scope give you a 60 MHz measurement capability. The combination will approximately equal the square root of the sum of the squares of the rise times (also see Chapter 10).

Figure 14.
PROBES CONNECT THE SCOPE AND THE CIRCUIT-UNDER-TEST. Tektronix probes consist of a patented resistive cable and a grounded shield. Two P6120 probes and the accessories pictured above are supplied with every 2200 Series scope. The probe is a high impedance, minimum loading 10 X passive probe. The accessories for each probe (from left to right) are: a grabber tip for ICs and small diameter leads; a retractable hook tip; and IC tester tip cover; an insulating ground cover; marker bands; and (in the center) the ground lead.

For example, if both probe and scope have rise times of 5.83 nanoseconds:

$$T_{r\,(system)} = \sqrt{T_{r\,(scope)}^2 + T_{r\,(probe)}^2}$$

$$T_r = \sqrt{34 + 34}$$

That works out to 8.25 nanoseconds, the equivalent to a bandwidth of 42.43 MHz because:

$$BW_{(megahertz)} = \frac{350}{T_{r\,(nanoseconds)}}$$

To get the full bandwidth from your scope, you need more bandwidth from the probe. Or you use the particular probe designed for that instrument. For example, in the case of the 2200 Series scopes and the P6120 10X Passive Probe, the probe and the scope have been designed to function together and you have the full 60 MHz bandwidth at the probe tip.

ALL ABOUT PROBES CONT.

Probe Types
Generally you can divide probes by function, into voltage-sensing and current-sensing types. Then voltage probes can be further divided into passive and active types. One of these should meet your measurement requirements.

PROBE TYPES	CHARACTERISTICS
1X passive, voltage-sensing	No signal reduction, which allows the maximum sensitivity at the probe tip; limited bandwidths: 4-34 MHz; high capacitance: 32-112 pF; signal handling to 500 V
10X/100X/1000X passive, voltage-sensing, attenuator	Attenuates signals; bandwidths to 300 MHz; adjustable capacitance; signal handling to 500 V (10X), 1.5 kV (100X), or 20 kV (1000X)
active, voltage-sensing, FET	Switchable attenuation; capacitance as low as 1.5 pF; more expensive, less rugged than other types; limited dynamic range; but bandwidths to 900 MHz; minimum circuit loading
current-sensing	Measure currents from 1 mA to 1000 A; DC to 50 MHz; very low loading
high voltage	Signal handling to 40 kV

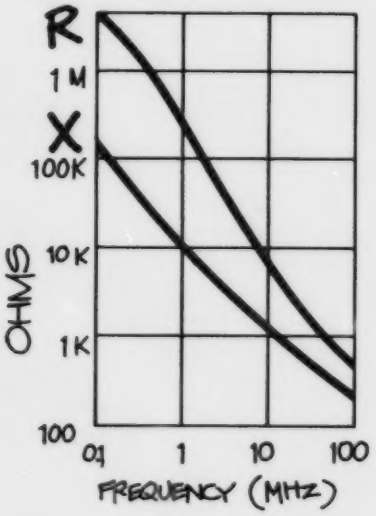


Figure 15.
PROBE IMPEDANCE IS RELATED TO FREQUENCY as shown in the table above. The curves plot both resistance (R) and reactance (X) in ohms against frequency in megahertz. The plot shown is for the Tektronix P6120 probe on a 1-meter cable.

Picking A Probe
For most applications, the probes that were supplied with your scope are the ones you should use. These will usually be attenuator probes. Then, to make sure that the probe can faithfully reproduce the signal for your scope, the compensation of the probe should be adjustable. If you're not going to use the probes that came with your scope, pick your probe based on the voltage you intend to measure. For example, if you're going to be looking at a 50 volt signal and your largest vertical sensitivity is 5 volts, that signal will take up ten major divisions of the screen. This is a situation where you need attenuation; a 10X probe would reduce the amplitude of your signal to reasonable proportions.

Proper termination is important to avoid unwanted reflections of the signal you want to measure within the cable. Probe/cable combinations designed to drive 1 megohm (1 MΩ) inputs are engineered to suppress these reflections. But for 50 Ω scopes, 50 Ω probes should be used. The proper termination is also necessary when you use a coaxial cable instead of a probe. If you use a 50 Ω cable and a 1 MΩ scope, be sure you also use a 50 Ω terminator at the scope input.

The probe's ruggedness, its flexibility, and the length of the cable can also be important (but remember, the more cable length, the more capacitance at the probe tip). And check the specifications to see if the bandwidth of the probe is sufficient, and make sure you have the adapters and tips you'll need. Most modern probes feature interchangeable tips and adaptors for many applications. Retractable hook tips let you attach the probe to most circuit components. Other adaptors connect probe leads to coaxial connectors or slip over square pins. Alligator clips for contacting large diameter test points are another possibility.

But for the reasons already mentioned (probe bandwidth, loading, termination), the best way to ensure that your scope and probe measurement system has the least effect on your measurements is to use the probe recommended for *your* scope. And always make sure it's compensated.

PART II. MAKING MEASUREMENTS

The first five chapters described how to select the exact oscilloscope functions you need to make the measurements you want. Now you can put what you've learned into practice with this section of the primer.

It begins with a review of waveform shapes and characteristics in Chapter 6. Then the discussions in Chapter 7 start with safety because you should always observe safety precautions when working on electrical equipment.

The first step in ensuring accurate measurements is making sure your scope is set up properly, and this subject is discussed in Chapter 8.

Chapter 9 discusses measurement techniques, beginning with fundamental time and amplitude measurements and ending with delayed sweep measurements.

The last chapter in the primer describes oscilloscope performance and how it affects your measurements.

CHAPTER 6. WAVEFORMS

The definition of a *wave* is "a disturbance traveling through a medium" while the definition of a *waveform* is "a graphic representation of a wave."

Like a wave, a waveform is dependent on two things: movement and time. The ripple on the surface of a pond exists as a movement of water in time. The waveform on your scope's screen is the movement of an electron beam during time.

The changes in the waveform with time form the waveshape, the most readily identifiable characteristic of a waveform. Figure 16 illustrates some common waveshapes.

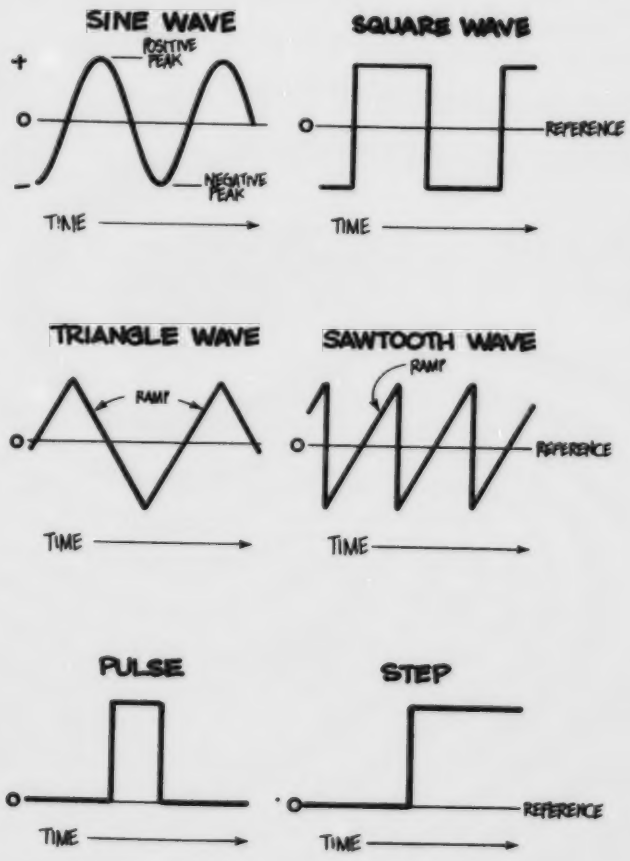


Figure 16.
BASIC WAVESHAPES include *sine waves*, and various non-sinusoidal waves such as *triangle waves*, *square waves*, and *sawtooth waves*. A square wave has equal amounts of time for its two states. Triangle and sawtooth waves are usually the result of circuits designed to control voltage with respect to time, like the sweep of an oscilloscope and some television circuits. In these waveforms, one (or both) transitions from state to state are made with a steady variation at a constant rate, a *ramp*. (Changes from one state to another on all waveforms except sine waves are called *transitions*.) The last two drawings represent aperiodic, single-shot waveforms. The first is a *pulse*; all pulses are marked by a rise, a finite duration, and a decay. The second one is a *step*, which is actually a single transition.

Waveshapes tell you a great deal about the signal. Anytime you see a change in the vertical dimension of a signal, you know that this amplitude change represents a change in voltage. Anytime there's a flat horizontal line, there was no change for that length of time. Straight diagonal lines mean a linear change, equal rise (or fall) of voltage for equal amounts of time. Sharp angles on a waveform mean a sudden change. But waveshapes alone are not the whole story. When you want to completely describe a waveform, you'll want to find the parameters of that particular waveform. Depending on the signal, these parameters might be amplitude, period, frequency, width, rise time, or phase. You can review these signal parameters with Figures 17 through 22.

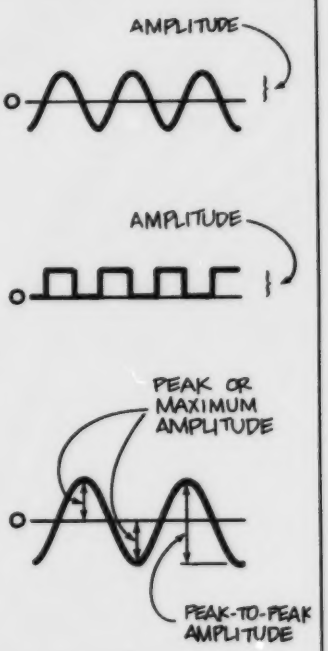


Figure 17.
AMPLITUDE IS A CHARACTERISTIC OF ALL WAVEFORMS. It is the amount of displacement from equilibrium at a particular point in time. Note that without a modifier, the word means the maximum change from a reference without regard to the direction of the change. In the first two drawings above (sine wave and square wave), the amplitude is the same even though the sine wave is larger from peak to peak. In the third drawing, an alternating current waveform is shown with peak (or maximum) amplitude and peak-to-peak amplitude parameters annotated. In oscilloscope measurements, amplitude usually means peak-to-peak amplitude.

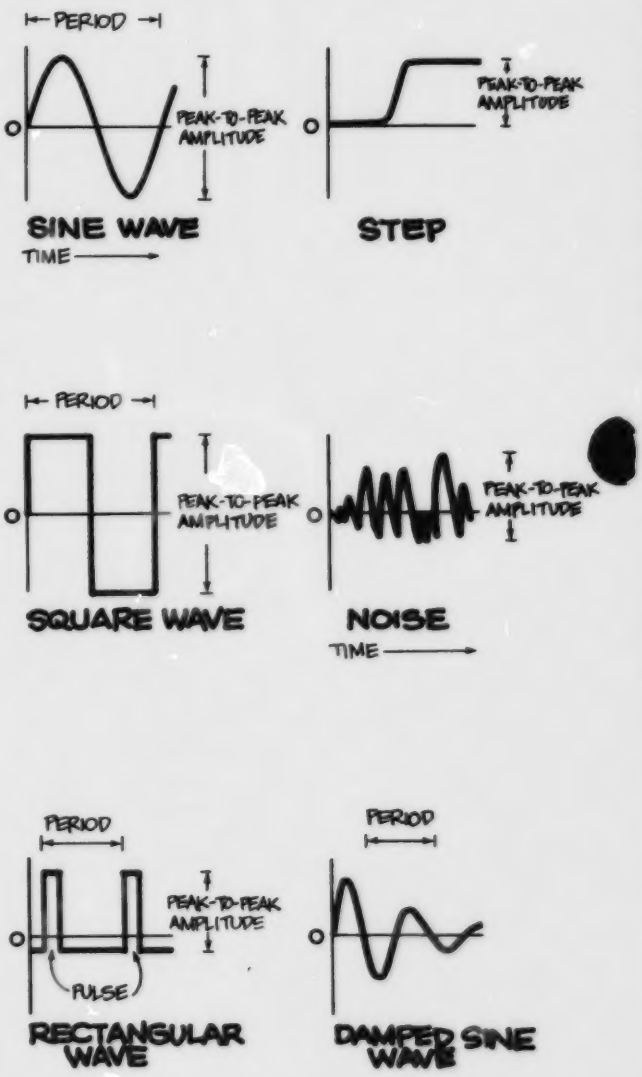


Figure 18.
PERIOD IS THE TIME REQUIRED FOR ONE CYCLE OF A SIGNAL if the signal repeats itself. Period is a parameter whether the signal is symmetrically shaped like the sine and square waves above, or whether it has a more complex and asymmetrical shape like the rectangular wave and damped sine wave. Period is always expressed in units of time. Naturally, one-time signals like the step or uncorrelated signals (without a time relation) like noise have no period.

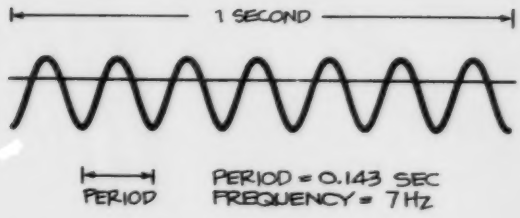


Figure 19.
IF A SIGNAL IS PERIODIC, IT HAS A FREQUENCY. Frequency is the number of times a signal repeats itself in a second; frequency is measured in Hertz: 1 Hz = 1 cycle per second; 1 kHz (kilohertz) = 1000 cycles/second; and 1 MHz (megahertz) = 1,000,000 cycles/second. Period and frequency are reciprocal: 1/period = frequency, and 1/frequency = period. For example, a 7 Hz signal has a period of 0.143 seconds: 1/7 Hz = 0.143 s, and 1/0.143 s = 7 Hz.

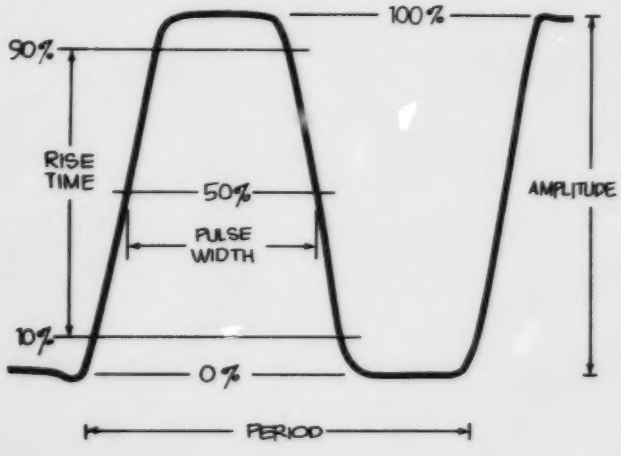


Figure 20.
THE PARAMETERS OF A PULSE can be important in a number of different applications. Digital circuitry, X-ray equipment, and data communications are examples. Pulse specifications include transition times measured on the leading edge of a positive-going transition; this is the *rise time*. *Fall time* is the transition time on a negative-going trailing edge. *Pulse width* is measured at the 50% points and amplitude from 0 to 100%. Any displacement from 0 volts for the base of the pulse is the *baseline offset*.

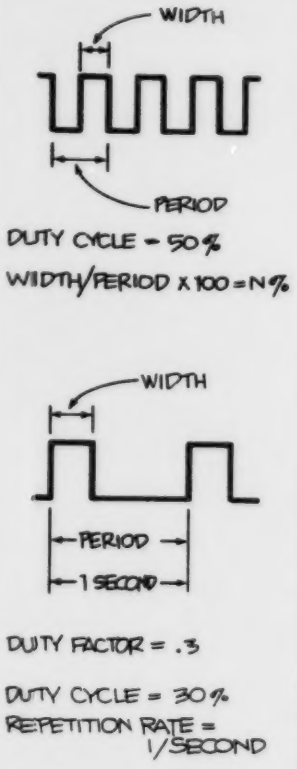


Figure 21.
DUTY CYCLE, DUTY FACTOR, AND REPETITION RATE are parameters of all rectangular waves. They are particularly important in digital circuitry. *Duty cycle* is the ratio of pulse width to signal period expressed as a percentage. For square waves, it's always 50% as you can see; for the pulse wave in the second drawing, it's 30%. *Duty factor* is the same thing as duty cycle except it is expressed as a decimal, not a percentage. A *repetition rate* describes how often a pulse train occurs and is used instead of frequency to describe waveforms like that in the second drawing.

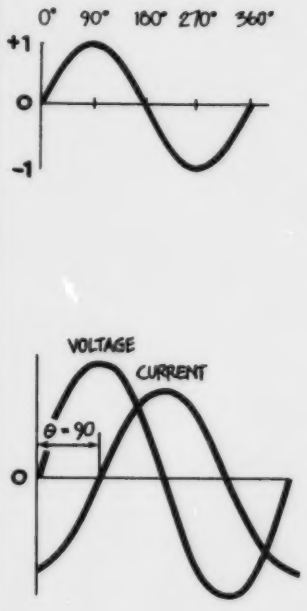


Figure 22.
PHASE is best explained with a sine wave. Remember that this waveform is based on the sine of all the angles from 0 through 360. The result is a plot that changes from 0 to 0°, 1 at 90°, 0 again at 180°, −1 at 270°, and finally 0 again at 360°. Consequently, it is useful to refer to the *phase angle* (or simply *phase*, when there is no ambiguity) of a sine wave when you want to describe how much of the period has elapsed. Another use of phase is found when you want to describe a relationship between two signals. Picture two clocks with their second hands sweeping the dial every 60 seconds. If the second hands touch the twelve at the same time, the clocks are *in phase*; if they don't, then they're *out of phase*. To express how far out of phase they are, you use *phase shift* in degrees. To illustrate, the waveform labeled CURRENT in the drawing above is said to be 90° out of phase with the voltage waveform. Other ways of reporting the same information are "the current waveform has a 90 degree phase angle with respect to the voltage waveform" or "the current waveform lags the voltage waveform by 90°." Note that there is always a reference to another waveform; in this case, between the voltage and current waveforms of an inductor.

CHAPTER 7. SAFETY

Before you make any oscilloscope measurement, remember that you must be careful when you work with electrical equipment. Always observe *all* safety precautions described in the operators or service manual for the equipment you're working on.

Some general rules about servicing electrical equipment are worth repeating here. Don't service electrical devices alone. Know the symbols for dangerous circuits and observe the safety instructions for the equipment you're working on. Don't operate an electrical device in an explosive atmosphere. Always ground the scope to the circuit, and ground both your scope and the circuit-under-test. Remember that if you lose the ground, all accessible conductive parts — including knobs that appear to be insulated — can give you a shock. To avoid personal injury, don't touch exposed connections and components in the circuit-under-test when the power is on. And remember to consult the service manual for the equipment you're working on.

Then there are few rules about the scope itself: To avoid a shock, plug the power cord of the scope into a properly-wired receptacle before connecting your probes; only use the power cord for your scope, and don't use one that isn't in good condition (cracked, broken, missing ground pin, etc.). Use the right fuse to avoid fire hazards. Don't remove covers and panels on your scope.

CHAPTER 8. GETTING STARTED

Accurate oscilloscope measurements require that you make sure your system is properly setup each time you begin to use your scope.

Compensating the Probe

Most measurements you make with an oscilloscope require an *attenuator probe*, which is any probe that reduces voltage. The most common are 10X ("times ten") passive probes which reduce the amplitude of the signal and the circuit loading by 10:1.

But before you make any measurement with an attenuator probe, you should make sure it's compensated. Figure 23 illustrates what can happen to the waveforms you'll see when the probe is not properly compensated.

Note that you should compensate your probe as it will be used when you make the measurement. Compensate it with the accessory tip you'll be using and don't compensate the probe in one vertical channel and then use it on another.

Checking the Controls

The most common mistake in making oscilloscope measurements is forgetting to compensate the probe. The second most frequent source of inaccuracies is forgetting to check the controls to make sure they're where you think they are. Here are some things to check on your Tektronix 2200 Series scope (arranged according to the functional blocks of your scope):

- Check all the vertical system controls: variable controls (CH 1 and CH 2 VOLTS/DIV CAL) should be in their calibrated detent positions; make sure CH 2 isn't inverted (unless you want it to be); check the vertical mode switches to make sure the signal from the proper channel(s) will be displayed; check the two vertical system VOLTS/DIV switches to see if their settings are right (and don't forget to use the VOLTS/DIV readout that matches the probe, either 1X or 10X); check the input coupling levers too.
- Check the horizontal system control settings: magnification is off (push in the red CAL switch in the middle of the SEC/DIV switch); variable SEC/DIV is in its calibrated detent position. Make sure the horizontal mode switch is where you need it: NO DLY when you're not making delayed sweep measurements, INTENS for making measurements with an intensified zone, or DLY'D if you want a delayed sweep (A, ALT, or B on a 2215).
- Then check your trigger system controls to make sure your scope will pick the right slope on the trigger signal, that the right coupling is selected, and that the correct operating mode will be used. Also make sure that the trigger variable holdoff control is at its minimum position.

Handling a Probe

Before you probe a circuit, you should make sure you have the right probe tips and adaptors for the circuits you will be working on. (Tips available for the Tektronix P6120 10X probes were shown in Figure 14, Chapter 5.)

Then make sure that the ground in the circuit-under-test is the same as the scope ground — don't just assume it is. The scope ground will always be earth ground as long as you're using the proper power cord and plug. Check the circuit ground by touching the probe tip to the point you think is ground before you make a hard ground by attaching the ground strap of your probe.

If you're going to be probing a lot of different points in the same circuit and measuring frequencies less than 5 MHz, you can ground that circuit to your scope once instead of each time you move the probe. Connect the circuit ground to the jack marked GND on the front panel.

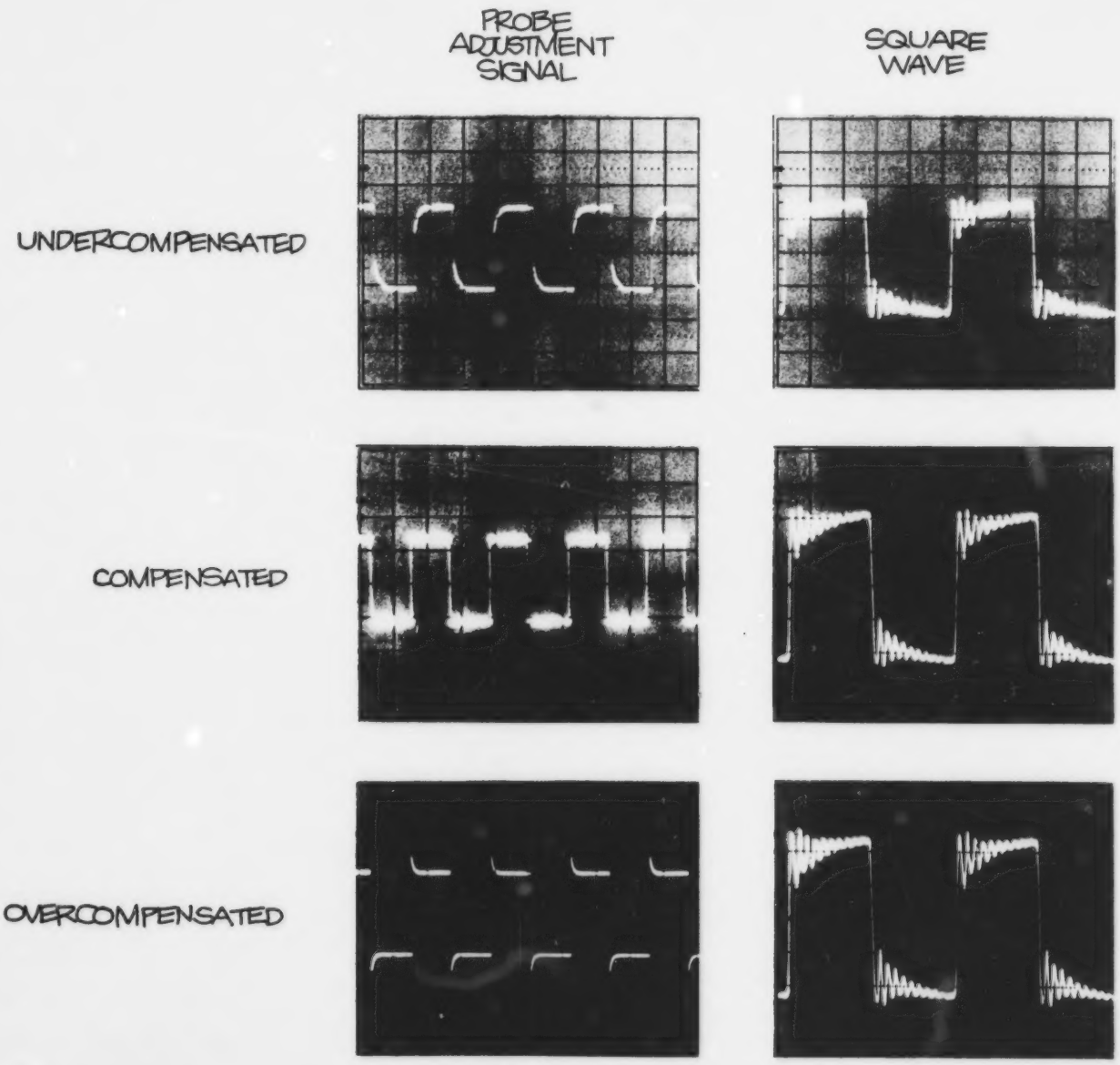


Figure 23.
IMPROPERLY COMPENSATED PROBES can distort the waveforms you see on the screen of your scope. In the photographs the probe adjustment signal and a 1 MHz square wave are shown as they will appear with proper and improper compensations. Notice the amplitude and ringing changes on the square wave with the differences in compensation.

CHAPTER 9. MEASUREMENT TECHNIQUES

Rather than attempt to describe how to make every possible measurement, this chapter describes common measurement techniques you can use in many applications.

The Foundations: Amplitude and Time Measurements

The two most basic measurements you can make are amplitude and time; almost every other measurement you'll make is based on one of these two fundamental techniques.

Since the oscilloscope is a voltage-measuring device, voltage is shown as amplitude on your scope screen. Of course, voltage, current, resistance, and power are related:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

$$\text{resistance} = \frac{\text{voltage}}{\text{current}}$$

$$\text{power} = \text{current} \times \text{voltage}$$

Amplitude measurements are best made with a signal that covers most of the screen vertically. Use Exercise 6 to practice making amplitude measurements.

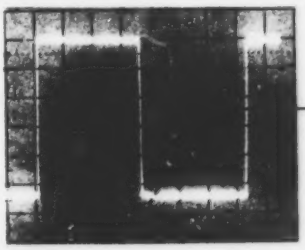
Time measurements are also more accurate when the signal covers a large area of the screen. Continue with the set-up you had for the amplitude measurement, but now use Exercise 7 to make a period measurement.

Exercise 6. AMPLITUDE MEASUREMENTS

1. Connect your probe to the channel 1 BNC connector and to the probe adjustment jack. Attach the probe ground strap to the collar of the channel 2 BNC. Make sure your probe is compensated and that all the variable controls are set in their detent positions.

2. The trigger MODE switch should be set to NORM for normal triggering. The HORIZONTAL MODE should be NO DLY (A on the 2215). Make sure the channel 1 coupling switch is set to AC and that the trigger SOURCE switch is on internal and the INT switch on CH 1. Set the VERTICAL MODE switch to CH 1 as well.

3. Use the trigger LEVEL control to obtain a stable trace and move the volts/division switch until the probe adjust square wave is about five divisions high. Now turn the seconds/division switch until two cycles of the waveform are on your screen. (The settings should be 0.1 V on the VOLTS/DIV and 0.2 ms on the SEC/DIV switches.)



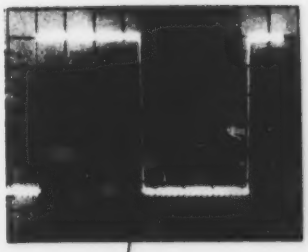
MAKE AMPLITUDE MEASUREMENTS ON THE CENTER VERTICAL GRATICULE LINE

4. Now use the CH 1 vertical POSITION control to move the square wave so that its top is on the second horizontal graticule line from the top edge of the screen. Use the horizontal position control to move the signal so that the bottom of one cycle intersects the center vertical graticule line.

5. Now you can count major and minor divisions down the center vertical graticule line and multiply by the VOLTS/DIV setting to make the measurement. For example, 5.0 divisions times 0.1 volts equals 0.5 volts. (If the voltage of the probe adjustment square wave in your scope is different from this example, that's because this signal is not a critical part of your scope and tight tolerances and exact calibration are not required.)

Exercise 7. TIME MEASUREMENTS

Time measurements are best made with the center horizontal graticule line. Use the instrument settings from Exercise 6 and center the square wave vertically with the vertical POSITION control. Then line up one rising edge of the square wave with the graticule line that's second from the lefthand side of the screen with the HORIZONTAL position control. Make sure the next rising edge intersects the center horizontal graticule. Count major and minor divisions across the center horizontal graticule line from left to right as shown in the photo above. Multiply by the SEC/DIV setting; for example, 5.7 divisions times 0.2 milliseconds equals 1.14 milliseconds. (If the period of the probe adjustment square wave in your scope is different from this example, remember that this signal is not a critical part the calibration of your scope.)



MAKE TIME MEASUREMENTS ON THE CENTER HORIZONTAL GRATICULE LINE

Frequency and Other Derived Measurements

The voltage and time measurements you just made are two examples of *direct measurements*. Once you've made a direct measurement, there are *derived measurements* you can calculate. Frequency is one example; it's derived from period measurements. While period is the length of time required to complete one cycle of a periodic waveform, frequency is the number of cycles that take place in a second. The measurement unit is a hertz (1 cycle/second) and it's the reciprocal of the period. So a period of 0.00114 second (or 1.14 milliseconds) means a frequency of 877 Hz.

More examples of derived measurements are the alternating current measurements illustrated by Figure 24.

Pulse Measurements

Pulse measurements are important when you work with digital equipment and data communications devices. Some of the signal parameters of a pulse were shown in Figure 20, but that was an illustration of an ideal pulse, not one that exists in the real world. The most important parameters of a real pulse are shown in Figure 25.

Use Exercise 8 to make derived measurements with the probe adjustment square wave.

Figure 24.
DERIVED MEASUREMENTS are the result of calculations made after direct measurements. For example, alternating current measurements require an amplitude measurement first. The easiest place to start is with a peak-to-peak amplitude measurement of the voltage — in this case, 330 volts because peak-to-peak measurements ignore positive and negative signs. The *peak voltage* is one-half that (when there is no DC offset), and is also called a *maximum value*; it's 165 V in this case. The *average value* is the total area under the voltage curves divided by the period in radians; in the case of a sine wave, the average value is 0 because the positive and negative values are equal. The RMS (root mean square) voltage for this sine wave — which represents the line voltage in the United States — is equal to the maximum value divided by the square root of 2: 165 ÷ 1.414 = 117 volts. You get from peak-to-peak to RMS voltage with: peak-to-peak ÷ 2 x the square root of 2.

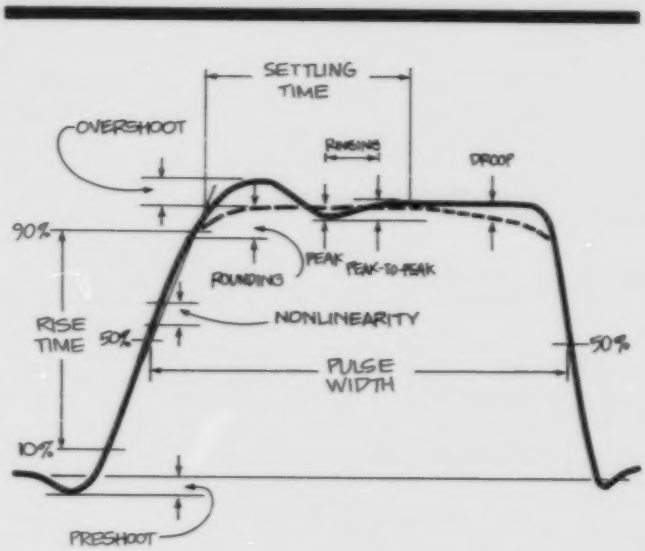


Figure 25.
REAL PULSE MEASUREMENTS include a few more parameters than those for an ideal pulse. In the diagram above, several are shown. Preshooting is a change of amplitude in the opposite direction that precedes the pulse. Overshooting and rounding are changes that occur after the initial transition. Ringing is a set of amplitude changes — usually a damped sinusoid — that follows overshooting. All are expressed as percentages of amplitude. Settling time expresses how long it takes the pulse to reach it maximum amplitude. Droop is a decrease in the maximum amplitude with time. And nonlinearity is any variation from a straight line drawn through the 10 and 90% points of a transition.

Exercise 8. DERIVED MEASUREMENTS

With the period measurement you just made in Exercise 7, calculate the frequency of the probe adjustment square wave. For example, if the period is 1 millisecond, then the frequency is the reciprocal, 1/0.001 or 1000 Hz. Other derived measurements you can make are duty cycle, duty factor, and repetition rate. Duty cycle is the ratio of pulse width to signal period expressed as a percentage: 0.5 ms ÷ 1 ms, or 50%. But you knew that because for square waves, it's always 50%. Duty factor is 0.5. And the repetition rate (describing how often a pulse train occurs) is 1000/second in this case because repetition rate and frequency are equal for square waves. Your probe adjustment signal might differ slightly from this example; calculate the derived measurements for it. You can also calculate the peak, peak-to-peak, and average values of the probe adjustment square wave in your scope. Don't forget that you need both the alternating and direct components of the signal to make these measurements, so be sure to use direct coupling (DC) on the vertical channel you're using.

Use the directions in Exercise 9 to make a pulse measurement on the probe adjustment square wave.

Exercise 9.
PULSE WIDTH MEASUREMENTS

To measure the pulse width of the probe adjustment square wave quickly and easily, set your scope to trigger on and display channel 1. Your probe should still be connected to the channel 1 BNC connector and the probe adjustment jack from the previous exercises. Use 0.1 ms/division and the no delay horizontal mode (A sweep if you're using a 2215). Use AUTO triggering on the positive slope and adjust the trigger LEVEL control to get as much of the leading edge as possible on your screen. Switch the coupling on channel 1 to ground and center the baseline on the center horizontal graticule. Now use AC coupling because that will center the signal on the screen and you make pulse width measurements at the 50% point of the waveform. Use your horizontal POSITION control to line up the 50% point with the first major graticule from the left side of the screen. Now you can count divisions and subdivisions across the center horizontal and multiply by the SEC/DIV switch setting to find the pulse width.

Phase Measurements

You know that a waveform has phase, the amount of time that has passed since the cycle began, measured in degrees. There is also a phase relationship between two or more waveforms: the phase shift (if any). There are two ways to measure the phase shift between two waveforms. One is by putting one waveform on each channel of a dual-channel scope and viewing them directly in the chop or alternate vertical mode; trigger on either channel. Adjust the trigger LEVEL control for a stable display and measure the period of the waveforms. Then increase the sweep speed so that you have a display something like the second drawing back in Figure 22. Then measure the horizontal distance between the same points on the two waveforms. The phase shift is the difference in time divided by the period and multiplied by 360 to give you degrees.

Displaying the two waveforms and measuring when one starts with respect to another is possible with any dual trace scope, but that isn't the only way to make a phase measurement. Look at the front panel and you'll see that the vertical channel BNC connectors are labeled X and Y. The last position on the SEC/DIV switch is XY, and when you use it, the scope's time base is bypassed. The channel 1 input signal is still the vertical axis of the scope's display, but now the signal on channel 2 becomes the horizontal axis. In the X-Y mode, you can input one sinusoidal on each channel and your screen will display a Lissajous pattern. (They are named for Jules Antoine Lissajous, a French physicist; say "LEE-za-shu"). The shape of the pattern will indicate the phase difference between the two signal. Some examples of Lissajous patterns are shown in Figure 26.

Note that general purpose oscilloscope Lissajous pattern phase measurements are usually limited by the frequency response of the horizontal amplifier (typically designed with far less bandwidth than vertical channels). Specialized X-Y scopes or monitors will have almost identical vertical and horizontal systems.

X-Y Measurements

Finding the phase shift of two sinusoidal signals with a Lissajous pattern is one example of an X-Y measurement. The X-Y capability can be used for other measurements as well. The Lissajous patterns can also be used to determine the frequency of an unknown signal when you have a known signal on the other channel. This is a very accurate frequency measurement as long as your known signal is accurate and both signals are sine waves. The patterns you can see are illustrated in Figure 26, where the effects of both frequency and phase differences are shown.

Component checking in service or production situations is another X-Y application; it requires only a simple transistor checker like that shown in Figure 27.

There are many other applications for X-Y measurements in television servicing, in engine analysis, and in 2-way radio servicing, for examples. In fact, any time you have physical phenomena that are interdependent and not time-dependent, X-Y measurements are the answer. Aerodynamic lift and drag, motor speed and torque, or

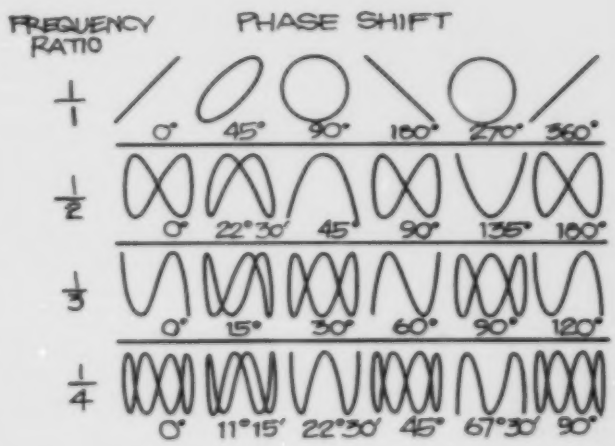


Figure 26.
FREQUENCY MEASUREMENTS WITH LISSAJOUS PATTERNS require a known wave on one channel. If there is no phase shift, the ratio between the known and unknown signals will correspond to the ratio of horizontal and vertical lobes of the pattern. When the frequencies are the same, only the shifts in phase will affect the pattern. In the drawings above, both phase and frequency differences are shown.

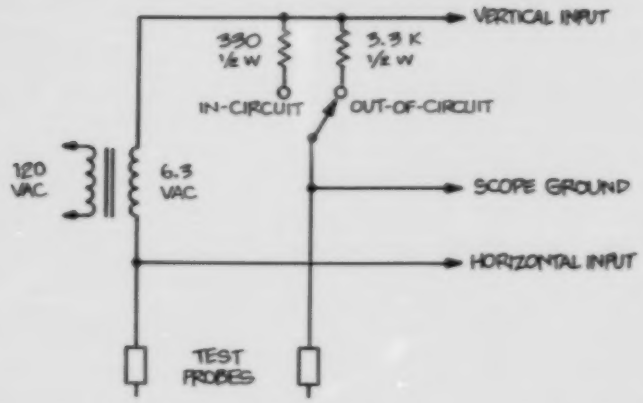


Figure 27.
X-Y COMPONENT CHECKING requires the transistor checker shown above. With it connected to your scope and the scope in the X-Y mode, patterns like those illustrated indicate the component's condition. The waveforms shown are found when the components are not in a circuit; in-circuit component patterns will differ because of resistors and capacitors associated with the component.

pressure and volume of liquids and gasses are more examples. With the proper transducer, you can use your scope to make any of these measurements.

Differential Measurements

The ADD vertical mode and the channel 2 INVERT button of your 2200 Series scope let you make differential measurements. Often differential measurements let you eliminate undesirable components from a signal that you're trying to measure. If you have a signal that's very similar to the unnecessary noise, the set up is simple. Put the signal with the spurious information on channel 1. Connect the signal that is like unwanted components to channel 2. Set both input coupling switches to DC (use AC if the DC components of the signal are too large), and select the alternate vertical mode by moving the VERTICAL MODE switches to BOTH and ALT.

Now set your volts/division switches so that the two signals are about equal in amplitude. Then you can move the right-hand VERTICAL MODE switch to ADD and press the INVERT button so that the common mode signals have opposite polarities.

If you use the channel 2 VOLTS/DIV switch and CAL control for maximum cancellation of the common signal, the signal that remains on-screen will only contain the desired part of the channel 1 input signal. The two common mode signals have cancelled out leaving only the difference between the two.

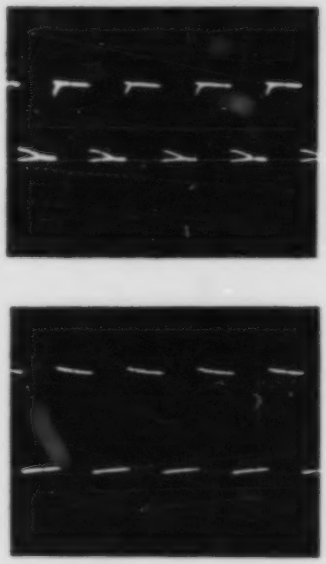


Figure 28.
DIFFERENTIAL MEASUREMENTS allow you to remove unwanted information from a signal anytime you have another signal that closely resembles the unwanted components. For example, the first photo shows a 1 kHz square contaminated by a 60 Hz sine wave. Once the common-mode componen: (the sine wave) is input to channel 2 and that channel is inverted, the signals can be added with the ADD vertical mode. The result is shown in the second photo.

Using the Z Axis

Remember from Part I that the CRT in your scope has three axes of information: X is the horizontal component of the graph, Y is the vertical, and Z is the brightness or darkness of the electron beam. The 2200 Series scopes all have an external Z-axis input BNC connector on the back of the instrument. This input lets you change the brightness (modulate the intensity) of the signal on the screen with an external signal. The Z-axis input will accept a signal of up to 30 V through a usable frequency range of DC to 5 MHz. Positive voltages decrease the brightness and negative voltages increase it; 5 volts will cause a noticeable change.

The Z-axis input is an advantage to users that have their instruments set up for a long series of tests. One example is the testing of high fidelity equipment illustrated by Figure 29.

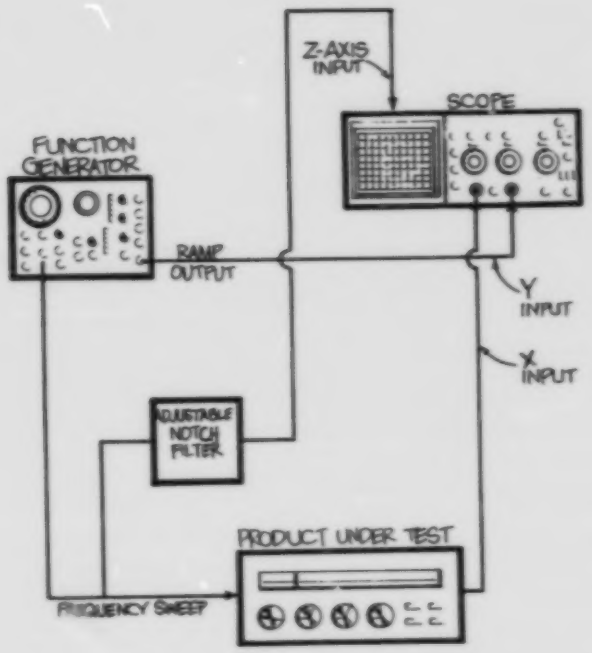


Figure 29.
USING THE Z-AXIS can provide additional information on the scope screen. In the set-up drawn above, a function generator sweeps through the frequencies of interest during the product testing — 20 to 20,000 Hz, in this case. Then an adjustable notch filter is used to generate a marker, at 15 kHz, for instance, and this signal is applied to the Z-axis input to brighten the trace. This allows the tester to evaluate the product's performance with a glance.

Using TV Triggering

The composite video waveform consists of two fields, each of which contains 262 lines. Many scopes offer television triggering to simplify looking at video signals. Usually, however, the scope will only trigger on fields at some sweep speeds and lines at others. The 2200 Series scopes allow you to trigger on either lines or fields at any sweep speed.

To look at tv fields with a 2200 Series scope, use the TV FIELD mode. This mode allows the scope to trigger at the field rate of the composite video signal on either field one or field two. Since the trigger system cannot recognize the difference between field one and field two, it will trigger alternately on the two fields and the display will be confusing if you look at one line at a time.

To prevent this, you add more holdoff time, and there are two ways to do that. You can use the variable holdoff control, or you can simply switch the vertical operating mode to display both channels. That makes the total holdoff time for one channel greater than one field period. Then just position the unused vertical channel off-screen to avoid confusion.

It is also important to select the trigger slope that corresponds to the edge of the waveform where the sync pulses are located. Picking a negative slope for pulses at the bottom of the waveform allows you to see as many sync pulses as possible.

When you want to observe the TV line portion of the composite video signal, use the NORM trigger mode and trigger on the horizontal synchronization pulses for a stable display. It is usually best to select the blanking level of the sync waveform so that the vertical field rate will not cause double triggering.

Delayed Sweep Measurements

Delayed sweep is a technique that adds a precise amount of time between the trigger point and the beginning of a scope sweep. Often delayed sweep is used as a convenient way to make a measurement (the rise time measurement in Exercise 10 is a good example). To make a rise time measurement without delayed sweep, you must trigger on the edge occurring before the desired transition. With delayed sweep, you may choose to trigger anywhere along the displayed waveform and use the delay time control to start the sweep exactly where you want.

Sometimes, however, delayed sweep is the *only* way to make a measurement. Suppose that the part of the waveform you want to measure is so far from the only available trigger point that it will not show on the screen. The problem can be solved with delayed sweep: trigger where you have to, and delay out to where you want the sweep to start.

But the delayed sweep feature you'll probably use the most often is the intensified sweep; it lets you use the delayed sweep as a positionable magnifier. You trigger normally and then use the scope's intensified horizontal mode. Now the signal on the screen will show a brighter zone after the delay time. Run the delay time (and the intensified zone) out to the part of the signal that interests you. Then switch to the delayed mode and increase the sweep speed to magnify the selected waveform portion so that you can examine it in detail.

Since the 2200 Series has two types of delayed sweep, read the paragraphs and use the delayed sweep measurement exercise below that applies to your scope: "Single Time Base Scopes" and Exercise 10 for delayed sweep measurements with single time base scopes like the Tektronix 2213; or "Dual Time Base Scopes" and Exercise 11 for delayed sweep on dual time base scopes like the 2215.

Single Time Base Scopes

Very few single time base scopes offer delayed sweep measurements. Those that do may have measurement capabilities similar to those of the Tektronix 2213 which has three possible horizontal operating modes annotated on the front panel as NO DLY, INTENS, and DLY'D.

When you set the HORIZONTAL MODE switch to NO DLY (no delay), only the normal sweep functions.

When you choose INTENS (intensified sweep), your scope will display the normal sweep and the trace will also be intensified after a delay time. The amount of delay is determined by both the DELAY TIME switch (you can use 0.5 μs, 10 μs, or 0.2 ms) and the DELAY TIME MULTIPLIER control. The multi-

plier lets you pick from 1 to 20 times the switch setting.

The third position, DLY'D (delayed), makes the sweep start after the delay time you've chosen. After selecting this position you can move the SEC/DIV to a faster sweep speed and examine the waveform in greater detail.

This list of horizontal modes should begin to give ideas of how useful these delayed sweep features are. Start by making the rise time measurement described below. (Note that when making rise time measurements, you *must* take the rise time of the measuring instrument into account. Be sure to read Chapter 10.)

Dual Time Base Scopes

Delayed sweep is normally found on dual time base scopes like the 2215 with two totally separate horizontal sweep generators. In dual time base instruments, one sweep is triggered in the normal fashion and the start of the second sweep is delayed. To keep these two sweeps distinct when describing them, the *delaying sweep* is called the *A sweep;* the *delayed sweep* is called the *B sweep*. The length of time between the start of the A sweep and the start of the B sweep is called the *delay time*.

Dual time base scopes offer you all the measurement capabilities of single time base instruments, plus:

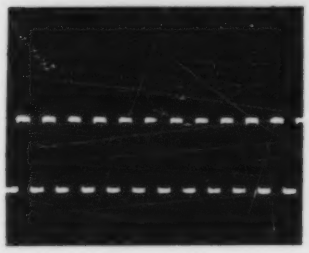
- convenient comparisons of signals at two different sweep speeds
- jitter-free triggering of delayed sweeps
- and timing measurement accuracy of 1.5%.

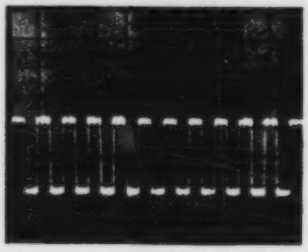
Most of this increase in measurement performance is available because you can separately control the two sweep speeds and use them in three horizontal operating modes. These modes — in a 2215 — are A sweep only, B sweep only, or A intensified by B as well as B delayed. The HORIZONTAL MODE switch controls the operating mode and two SEC/DIV switches — concentrically mounted on a 2215 — control the sweep speeds. See Figure 30.

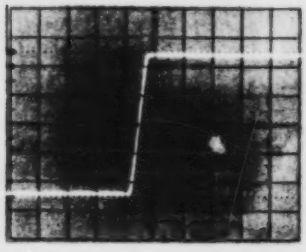
When you use the ALT (for alternate horizontal mode) position the HORIZONTAL MODE switch, the scope will display the A sweep intensified by the B sweep and the B sweep delayed. As you set faster sweeps with the B SEC/DIV switch, you'll see the intensified zone on the A trace get smaller and the B sweep expanded by the new speed setting. As you move the B DELAY TIME POSITION dial and change where the B sweep starts, you'll see the intensified zone move across the A trace and see the B waveform change.

This sounds more complicated in words than it is in practice. As you use the scope in Exercise 11, you'll find that the procedure is very easy. You will always see exactly where the B sweep starts. And you can use the size of the intensified zone to judge which B sweep speed you need to make the measurement you want.

Exercise 10. 2213 DELAYED SWEEP MEASUREMENTS







1. *Connect your probe to the channel 1 BNC connector and the probe adjustment jack, hook the ground strap onto the collar of the channel 2 BNC, and make sure the probe is compensated.*
2. *Use these control settings: CH 1 VOLTS/DIV on 0.2 using the 10X probe VOLTS/DIV readout; CH 1 input coupling on AC; VERTICAL MODE is CH 1; TRIGGER MODE is AUTO; TRIGGER SLOPE is negative (−); trigger SOURCE is INT (for internal) and INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is NO DLY; SEC/DIV is 0.5 ms. Check all the variable controls to make sure they're in their calibrated detent positions.*
3. *Set the input coupling to GND and center the trace. Switch back to AC and set the trigger LEVEL control for a stable display. The waveform should look like the first photo above.*
4. *Because a rise time measurement is best made at faster sweep speeds, turn the SEC/DIV control to 2 μs. Use the trigger LEVEL control to try to get all of the positive transition on the screen. You can't; you lose your trigger when you get off the slope of the signal.*
5. *Turn back to 0.5 ms/div and switch to the intensified display with the HORIZONTAL MODE switch. Switch the DELAY TIME to 0.2 ms and use the DELAY TIME MULTIPLIER to move the intensified zone on the waveform to a point before the first complete positive-going transition of the square wave. The intensified zone now shows you where the delayed sweep will start, like the second photo.*
6. *Switch the horizontal mode to DLY'D and the SEC/DIV switch to 5 μs. Now you can use the horizontal POSITION and DELAY TIME MULTIPLIER controls to get a single transition on the screen.*
7. *Change to 0.1 V/div and line up the signal with the 0 and 100% dotted lines of the graticule. (If you have a signal that doesn't fit between the 0 and 100% lines of the graticule, you have to count major and minor divisions and estimate the rise time while ignoring the first and last 10% of the transition.)*
8. *Use the horizontal POSITION control to move the waveform until it crosses a vertical graticule line at the 10% marking. Adjust the FOCUS control for a sharp waveform and make your rise time measurement from that vertical line to where the step crosses the 90% line. Now you can make a rise time measurement on a waveform like that in the third photograph. For example, for 1 major division and 4 minor divisions: 1.8 times the SEC/DIV setting of 5 μs is 9 μs.*

Measurements at Two Sweep Speeds

Looking at a signal with two different sweep speeds makes complicated timing measurements easy. The A sweep gives you a large slice of time on the signal to examine. The intensified zone will show you where the B sweep is positioned. And the faster B sweep speeds magnify the smaller portions of the signal in great detail. You'll find this capability useful in many measurement applications; see Figure 31 for two illustrations.

Because you can use the scope to show A and B sweeps from both channel 1 and channel 2, you can display four traces. To prevent overlapping traces, most dual time base scopes offer an additional position control. On the 2215, it's labeled ALT SWP SEP for *alternate sweep separation*. With it and the two vertical channel POSITION controls, you can place all four traces on-screen without confusion.

Separate B Trigger

Jitter can prevent an accurate measurement anytime you want to look at a signal that isn't perfectly periodic. But with two time bases and delayed sweep, you can solve the problem with the separate trigger available for the B sweep. You trigger the A sweep normally and move the intensified zone out to the portion of the waveform you want to measure. Then you set the scope up for a triggered B sweep, rather than letting the B sweep simply run after the delay time.

On a 2215, the B TRIGGER LEVEL control does double duty. In its full clockwise position, it selects the run-after-delay mode. At any other position, it functions as a trigger level control for the B trigger. The B TRIGGER SLOPE control lets you pick positive or negative transitions for the B trigger.

With these two controls you can trigger a stable B sweep even when the A sweep has jitter.

Increased Timing Measurement Accuracy

Besides examining signals at two different sweep speeds and seeing a jitter-free B sweep, you get increased timing measurement accuracy with a dual time base scope.

Note that the B DELAY TIME POSITION dial is a measuring indicator as well as a positioning device. The numbers in the window at the top of the dial are calibrated to the major divisions of the scope screen. The numbers around the circumference divide the major division into hundreds.

To make timing measurements accurate to 1.5% with the B DELAY TIME POSITION dial:

- use the B runs-after-delay mode.
- place the intensified zone (or use the B sweep waveform) where the timing measurement begins, and note the B DELAY TIME POSITION dial setting
- dial back to where the measurement ends and note the reading there
- subtract the first reading from the second and multiply by the A sweep SEC/DIV setting.

You'll find an example of this accurate — and easy — timing measurement in Exercise 11.

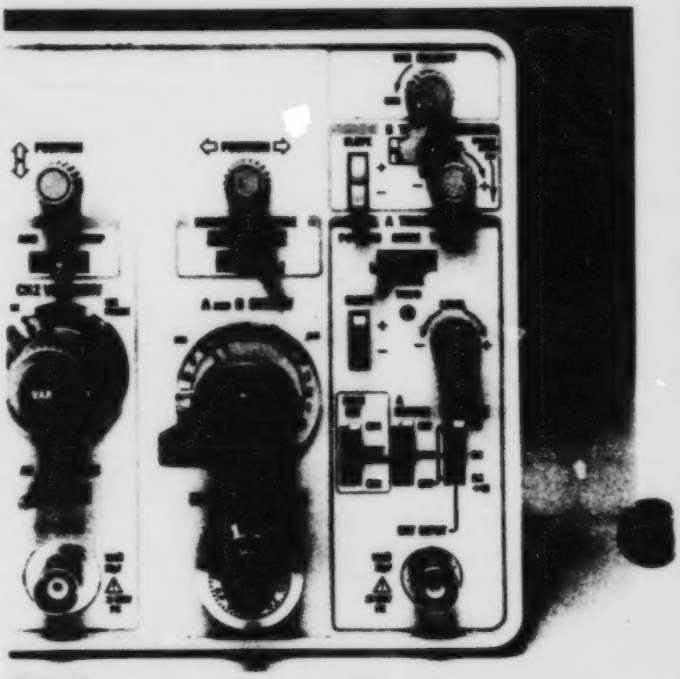


Figure 30.
THE DELAYED SWEEP CONTROLS of the dual time base 2215 are shown on the photograph above. They include: HORIZONTAL MODE (under the horizontal POSITION control); B TRIGGER SLOPE and LEVEL; ALT SWP SEP (alternate sweep separation, between the two vertical POSITION controls — not shown), and a concentric A and B SEC/DIV control. The B DELAY TIME POSITION dial is at the bottom of the column of horizontal system controls.

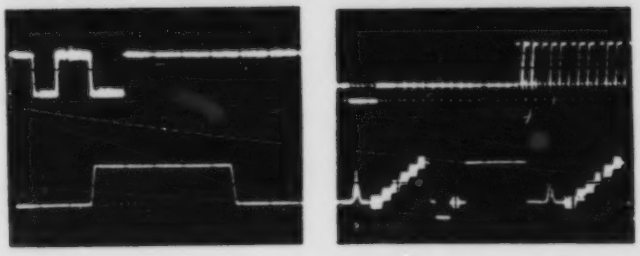
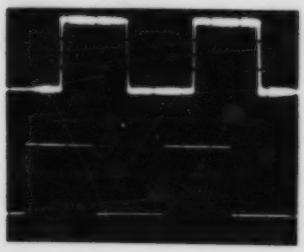
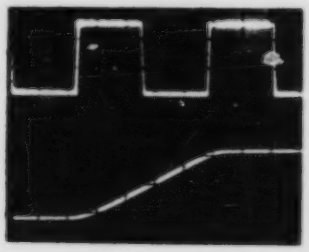


Figure 31.
ALTERNATE DELAYED SWEEP MEASUREMENTS are fast and accurate. One use, examining timing in a digital circuit, is demonstrated in the first photograph. Suppose you need to check the width of one pulse in a pulse train like the one shown. To make sure which pulse you are measuring, you want to look at a large portion of a signal. But to measure the one pulse accurately, you need a faster sweep speed. Looking at both the big picture and a small enlarged portion of the signal is easy with alternate delayed sweep. Another example is shown in the second photo. Here one field of composite video signal is shown in the first waveform. The intensified portion of the field is the lines magnified by the faster B sweep. With a dual time base scope, you can walk through the field with the B DELAY TIME POSITION dial and look at each line individually.

Exercise 11. 2215 DELAYED SWEEP MEASUREMENTS

Rise Time Measurement





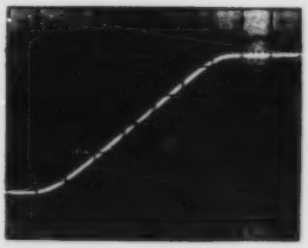
1. *Connect your probe to the channel 1 BNC connector and the probe adjustment jack, hook the ground strap onto the collar of the channel 2 BNC, and make sure the probe is compensated. Use these control settings: CH 1 VOLTS/DIV on 0.2 (remember to use the 10X probe readout); CH 1 input coupling on AC; VERTICAL MODE is CH 1; A TRIGGER MODE is NORM; A TRIGGER SLOPE is negative (−); A SOURCE is INT and the A&B INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is A; A and B SEC/DIV is 0.2 ms. Check the variable controls to make sure they're in their calibrated detent positions.*

3. *Set the A TRIGGER LEVEL control for a stable display and position the waveform in the top half of the screen. Switch to the ALT (for alternate A and B sweeps) display with the HORIZONTAL MODE switch. Use the channel 1 POSITION and ALT SWP SEP (alternate sweep separation) controls to position the two sweeps so that they don't overlap.*

4. *Use the B DELAY TIME POSITION dial to move the beginning of the intensified zone a point before the first complete positive transition. Your screen should look like the first photo above.*

5. *Pull out on the SEC/DIV knob and rotate it clockwise to change the B sweep speed to 2 µs/division. This will make the intensified zone smaller; move it to the first rising edge of the waveform as in the second photograph.*

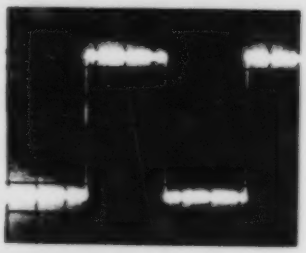
6. *Switch the horizontal mode to B, the channel 1 vertical sensitivity to 0.1 volts/division, and the sweep speed to 1 µs/division. Use the horizontal and vertical POSITION controls and the B DELAY TIME POSITION control to line up the waveform with the 0 and 100% dotted lines of the graticule. (If you have a signal that doesn't fit between the 0 and 100% lines of the graticule, you have to count major and minor divisions and estimate the rise time while ignoring the first and last 10%.)*

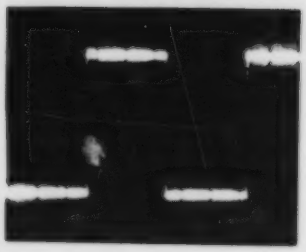


7. *Position the waveform so that it crosses a vertical graticule line at the 10% marking. Adjust the FOCUS control for a sharp waveform and count major and minor divisions across the screen to where the step crosses the 90% line. If there are 4 major and 8 minor divisions, 4 and 8/10 times the SEC/DIV setting of 1 µs is 4.8 µs. The third photo shows how the screen should look now. (Note: Any jitter you see in the B sweep is from the probe adjustment circuit, not the time base.)*

8. *One last word on rise time measurements: the accuracy of the measurement you make depends on both the signal you're examining and the performance of your scope. In Chapter 10, you'll find a description of how the scope's own rise time affects your measurement results.*

Pulse Width Measurement





1. *Use these control settings: CH 1 VOLTS/DIV on 0.1; CH 1 input coupling on AC; VERTICAL MODE is CH 1; A TRIGGER MODE is NORM; A TRIGGER SLOPE is negative (−); A TRIGGER SOURCE is INT (for internal) and INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is A; A SEC/DIV is 0.2 ms while B SEC/DIV is 0.05 µs. Check the variable controls.*

2. *Center the first complete pulse of the waveform horizontally. Switch to the ALT display with the HORIZONTAL MODE switch and move the B waveform to the bottom of the screen with the ALT SWP SEP control.*

3. *Center A sweep waveform vertically. Turn down the intensity so that it's easier to see the small intensified zone.*

4. *Move the intensified zone to the 50% point of the rising edge of the waveform with the DELAY TIME POSITION control as in the first photo above. Note the delay time reading (the number in the window first, for example: 3.1). Move the intensified zone to the 50% point of the trailing edge as in the second photo and note the reading.*

5. *The time measurement, a pulse width in this case, is equal to the second dial reading minus the first times the A sweep speed: 5.77 − 3.13 x 0.2 ms = 0.528 ms. In other words, the B DELAY TIME POSITION dial indicates screen divisions for you, 1 complete turn for every major division.*

CHAPTER 10. SCOPE PERFORMANCE

There are two aspects to oscilloscope performance: the design parameters of the instrument, and its conformance to those parameters at the time you are making measurements. Making the instrument conform to its design parameters simply means calibration — including making sure the probe is properly compensated as you've done many times already. But even with proper calibration, there will be some effect of the designed performance on your measurements.

Square Wave Response and High Frequency Response

In the design of amplifiers like those in a scope's vertical channels, there is always some compromise between the circuit's high frequency response and its handling of signals with square transitions. Extending the frequency response can be accomplished with high frequency compensation, but too much compensation results in overshoot on a step. Too little extends the measured rise time. The best rise times without overshoot are achieved when the high frequency response is critically damped; the frequency response then falls off smoothly. Figure 32 illustrates the effects of high frequency compensation.

Instrument Rise Time and Measured Rise Times

The rise time of an oscilloscope is a very important specification because the measuring instrument's rise time affects the accuracy of your measured rise times as expressed by this approximation:

$$T_{r\,(measurement)} = \sqrt{T_{r\,(signal)}^{2} + T_{r\,(measuring\ system)}^{2}}$$

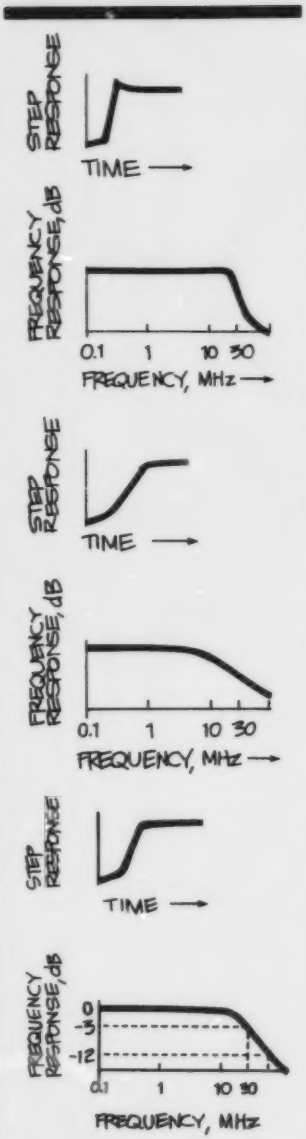


Figure 32.
HIGH FREQUENCY COMPENSATION in a scope's vertical amplifier has an effect on the rise time of square waves measured by the scope. If too much high frequency compensation is present, the rise times will show overshoot and possible ringing, as in the top drawing. Too little, as shown in the second drawing, tends to rolloff the edges of the square wave. A critically damped frequency response is best as in the third drawing.

In practical terms this means that the accuracy of a measured signal will be predictable and will be dependent on how much faster your scope is than the rise time you're measuring. If the measuring scope is five times faster than the observed signal, the measurement error can be as low as 2%. For measurement accuracies of 1%, it takes a scope 7 times faster, as you can see on the chart in Figure 33.

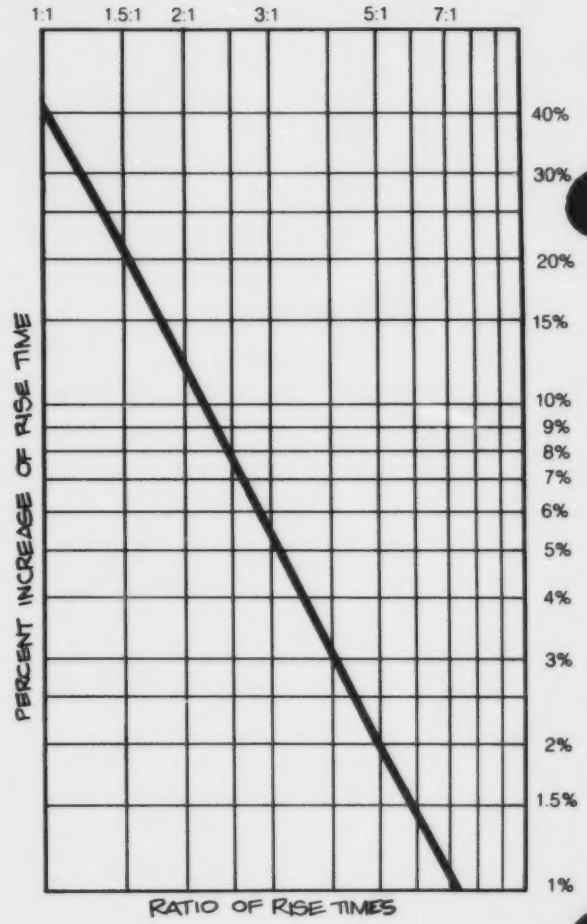


Figure 33.
MEASURED RISE TIME ERRORS depend on the ratio of the measuring system's rise time to the rise time of the signal being measured. As you can see from the chart, when the scope is five times faster the error is a 2% increase in the measured rise time. If the rise times are equal, the error is a 41% increase.

Bandwidth and Rise Time

The vertical channels of an oscilloscope are designed for a broad bandpass, generally from some low frequency (DC) to a much higher frequency. This is the oscilloscope's bandwidth, specified by listing the frequency at which a sinusoidal input signal has been attenuated to 0.707 of the middle frequencies; this is called the −3 dB point. For older instruments, specifications cited both a low and high −3 dB point. Modern instruments, however, have a relatively flat frequency response down to 0 Hz (DC), so only the upper number is quoted as the bandwidth.

A bandwidth specification gives you an idea of instrument's ability to handle high frequency signals within a specified attenuation. But bandwidth specifications are derived from the instrument's ability to display sine waves. A 35 MHz scope will show a 35 MHz sine wave with only −3 dB attenuation, but the effects on a square wave at or near the scope's upper bandwidth limit will be much more severe because high frequency information in the square wave will not be accurately reproduced by the scope. See Figure 34 for an example.

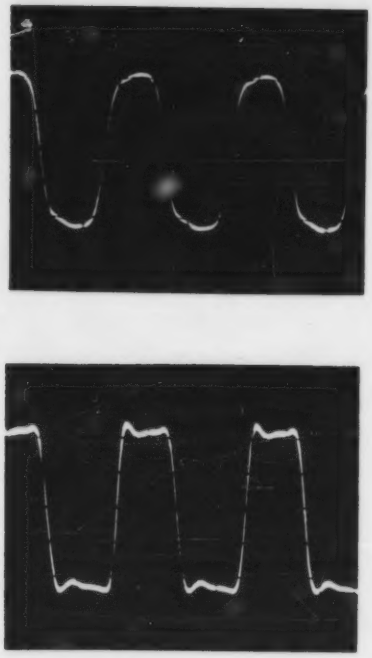


Figure 34.
BANDWIDTH SPECIFICATIONS are based on the scope's ability to reproduce sine waves. The upper bandwidth is the frequency at which a sine wave is reduced to 0.707 of the amplitude shown at middle frequencies. Though this specification tells you how well the instrument reproduces sine waves, not every signal you examine is sinusoidal. Square waves, for example, have a great deal of high frequency information in their rising and falling edges that will be lost as you approach the bandwidth limits of the instrument. To illustrate, the two CRT photos show a 15 MHz square wave reproduced by a 35 MHz (top) and 60 MHz (bottom) oscilloscopes.

The frequency response of most scopes is designed so that there is a constant that allows you to relate the bandwidth and rise time of the instrument. This constant is 0.35 and the rise time and bandwidth are related by this approximation:

$$T_r = \frac{0.35}{BW}$$

A simple way to apply the formula is:

$$T_{r\ (nanoseconds)} = \frac{350}{BW_{(megahertz)}}$$

For the Tektronix 2200 Series instruments with a bandwidth of 60 MHz, the rise time is 5.8 nanoseconds.

CONCLUSION

This concludes your introduction to oscilloscopes and the measurements you can make with scopes. You've done well to progress this far, but this primer can only introduce the concepts and measurement techniques. With practice and experience, you'll find yourself making faster and more accurate measurements. Then you too will find that using an oscilloscope is second nature to you.

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TEK

Tektronix incorporated in 1946 and since then has grown to be the largest manufacturer of oscilloscopes in the world. The list of innovations pioneered by Tek includes: triggered sweeps, calibrated time bases, low-loading probes, bistable and fast-transfer storage. Included in Tek's broad measurement instrument offerings are:

- Portable scopes small enough to hold in your hand or fast enough to measure 350 MHz signals.
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- And accessories to support these instruments including probes, cameras, cables, and scope carts.

Behind all these products is the world-wide Tektronix sales and service organization with 45 offices in the United States and over a hundred in 65 other countries around the world.

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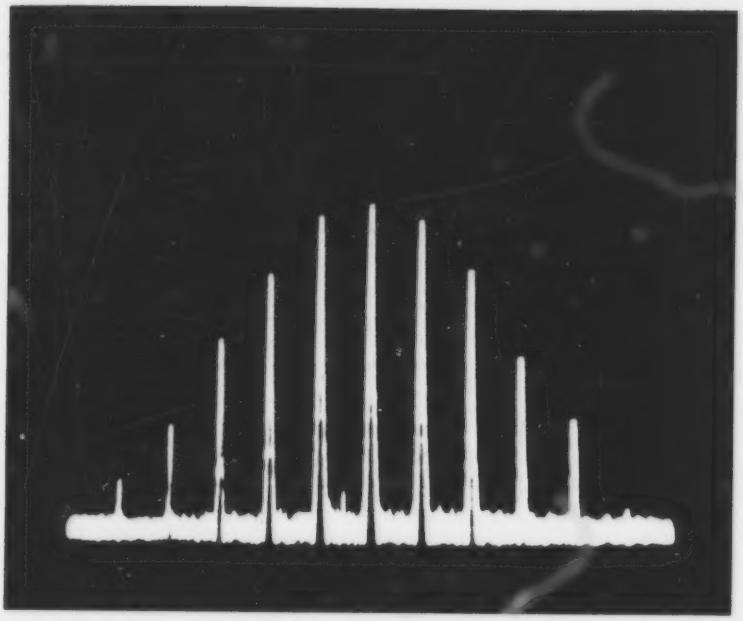

Spectrum Analyzer Series

APPLICATION NOTE 150

SPECTRUM ANALYSIS....

Spectrum Analyzer Basics

HEWLETT PACKARD

April 1974

APPLICATION NOTE 150

Printed April 1974

HEWLETT PACKARD

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The traditional way of observing electrical signals is to view them in the time domain using an oscilloscope. The time domain is used to recover relative timing and phase information which is needed to characterize electric circuit behavior. However, not all circuits can be uniquely characterized from just time domain information. Circuit elements such as amplifiers, oscillators, mixers, modulators, detectors and filters are best characterized by their frequency response information. This frequency information is best obtained by viewing electrical signals in the frequency domain. One instrument which displays the frequency domain is the spectrum analyzer.

The frequency domain is a graphical representation of signal amplitude as a function of frequency. Figure 1.1 illustrates the relationship between the time domain and the frequency domain. In the time domain, all frequency components of a signal are seen summed together. In the frequency domain, complex signals (i.e., signals composed of more than one frequency) are separated into their frequency components, and the power level at each frequency is displayed.

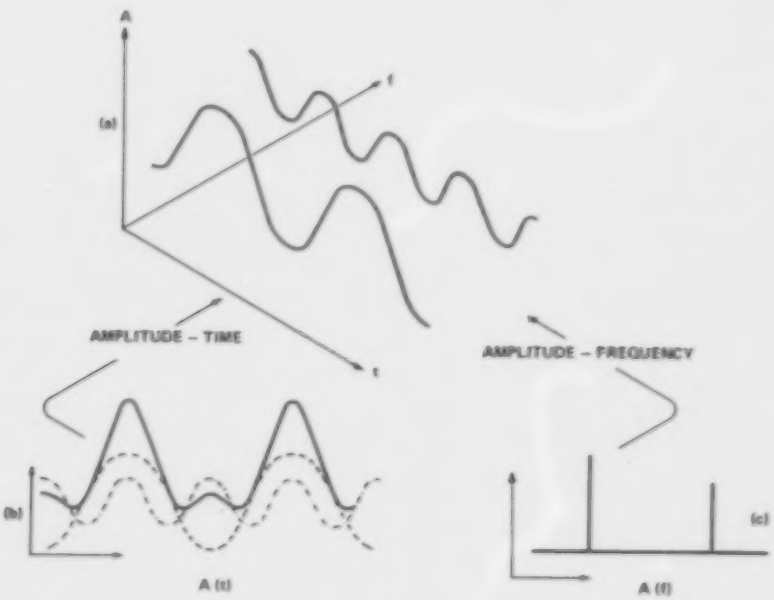


Figure 1.1 Relationship between the time and frequency domains: (a) Three-dimensional coordinates showing time, frequency, and amplitude. The addition of a fundamental and its second harmonic is shown as an example. (b) View seen in the time domain. On an oscilloscope, only the composite $f_1 + 2F_1$ would be seen. (c) View seen in the frequency domain. The components of the composite signal are clearly seen here.

To display the frequency domain requires a device that can discriminate between frequencies while measuring the power level at each. The spectrum analyzer was designed for this purpose. A spectrum analyzer is an instrument which graphically displays voltage or power as a function of frequency on a CRT (cathode ray tube). It can be used to analyze signals in the frequency domain.

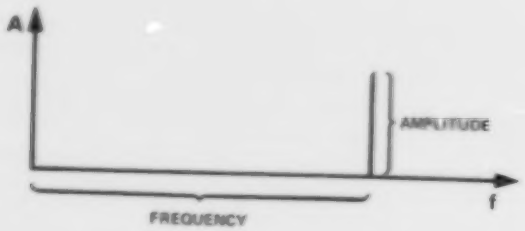


Figure 1.2 Frequency domain display of a CW signal.

The frequency domain contains information not found in the time domain and therefore, the spectrum analyzer has certain advantages not available with an oscilloscope. Following is an outline of spectrum analyzer applications. These are described in more detail in the following brochures:

The Spectrum Analyzer for Design Engineers (HP Lit. No. 5952-0932)
The Spectrum Analyzer Could Be the Most Important Test Instrument On Your Bench (HP Lit. No. 5952-9201)
AN-150 Series

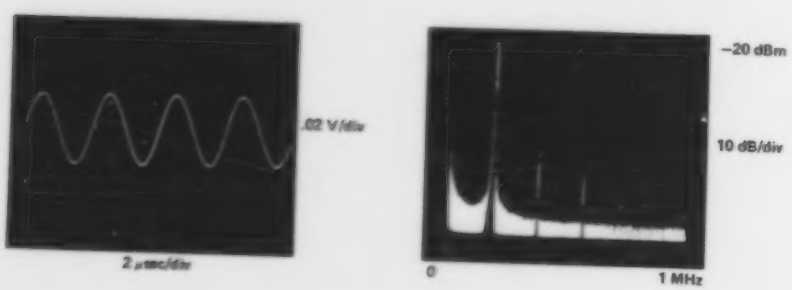


Figure 1.3

1. The analyzer is more sensitive to low level distortion than a scope. The sine wave in Figure 1.3 looks good in the time domain, but in the frequency domain, harmonic distortion can be seen.

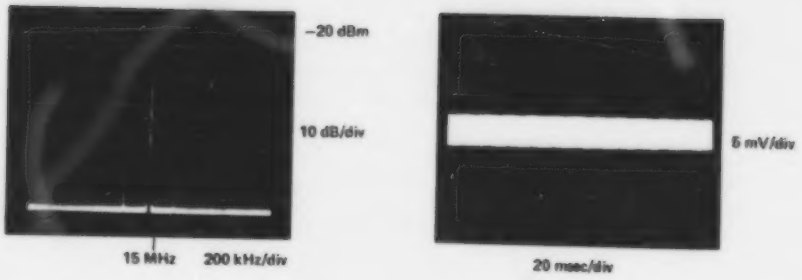


Figure 1.4

2. The sensitivity and wide dynamic range of the analyzer is useful for measuring low-level modulation. In Figure 1.4 the 2% AM can be measured easily with the spectrum analyzer where it can barely be seen with an oscilloscope.

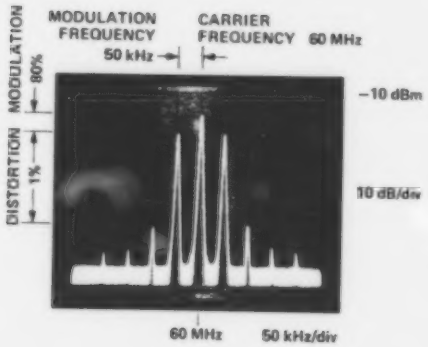


Figure 1.5

3. The spectrum analyzer can be used to measure AM, FM and pulsed RF. Figure 1.5 shows how the analyzer can be used to measure carrier frequency, modulation frequency, modulation level, and modulation distortion.

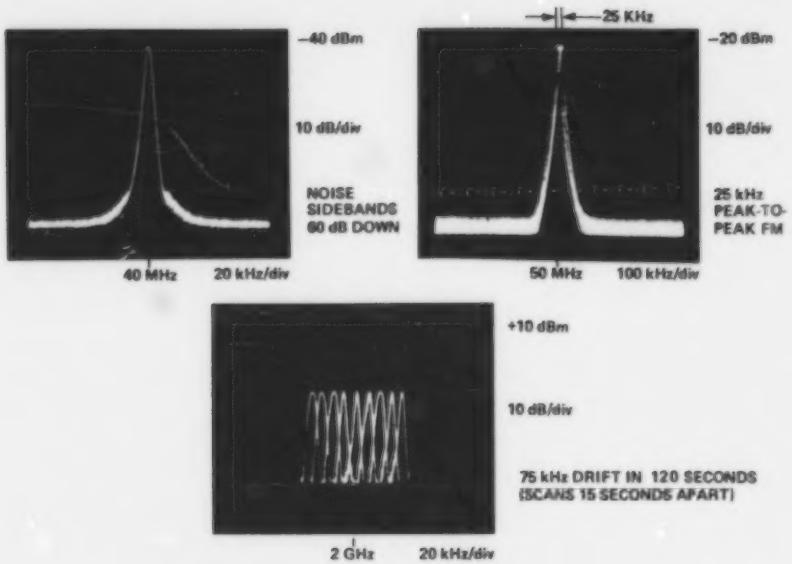


Figure 1.6

4. The spectrum analyzer can be used to measure long and short term stability. Parameters such as noise sidebands on an oscillator, residual FM of a source and frequency drift during warm-up can be measured using the spectrum analyzer's calibrated scan times. These parameters are shown in Figure 1.6.

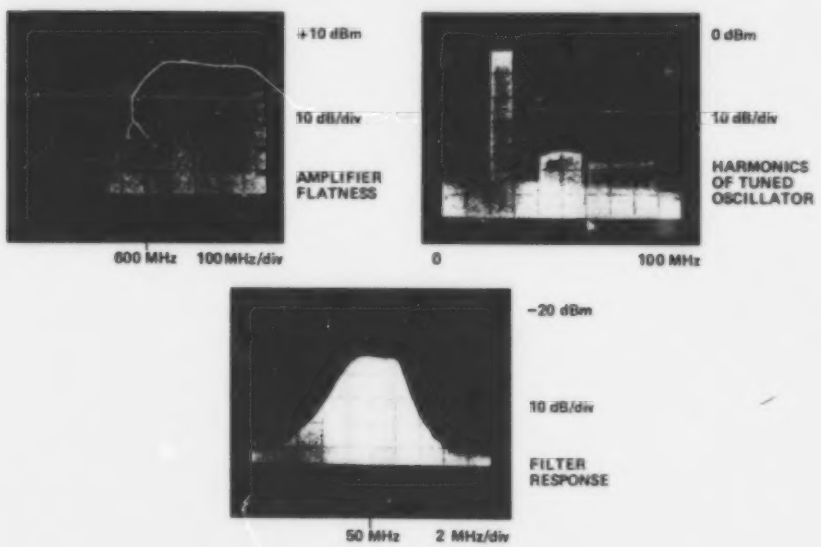


Figure 1.7

5. The swept frequency response of a filter or amplifier and the swept distortion measurement of a tuned oscillator are examples of swept frequency measurements possible with a spectrum analyzer, as shown in Figure 1.7. These measurements are simplified by using a variable persistence display or a tracking generator which will be described later.

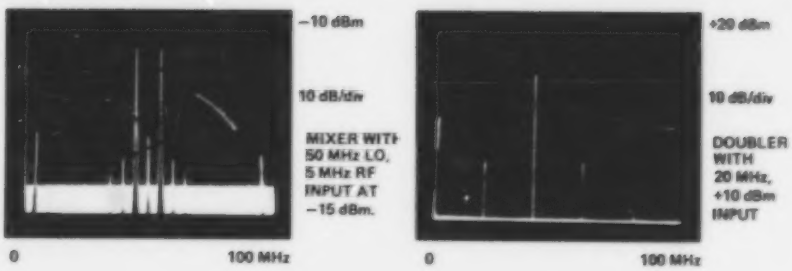


Figure 1.8

6. Frequency conversion devices can be easily characterized with a spectrum analyzer. Such parameters as conversion loss, isolation, and distortion are readily determined from the display.

There are two basic types of spectrum analyzers, swept-tuned and real-time analyzers. The swept-tuned analyzers are tuned by electrically sweeping them over their frequency range. Therefore, the frequency components of a spectrum are sampled sequentially in time.

This enables periodic and random signals to be displayed, but makes it impossible to display transient responses. Real-time analyzers, on the other hand, simultaneously display the amplitude of all signals in the frequency range of the analyzer; hence the name real-time. This preserves the time dependency between signals which permits phase information to be displayed. Real-time analyzers are capable of displaying transient responses as well as periodic and random signals.

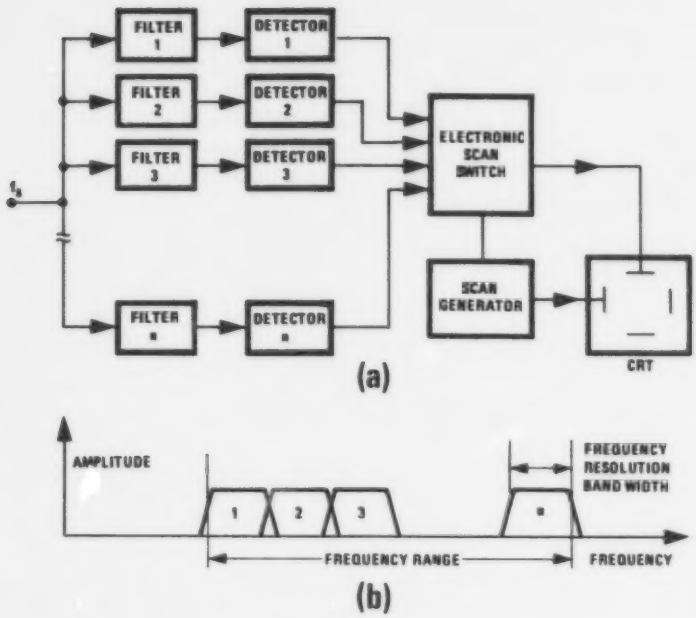


Figure 1.9 (a) Block diagram of a real-time spectrum analyzer. The electronic scan switch samples the filters fast enough to display the instantaneous response of the input signals. (b) The bandpass filters are staggered to permit continuous coverage of the frequency spectrum.

A real-time or multichannel analyzer is basically a set of staggered bandpass filters as shown in Figure 1.9. The composite amplitude of the signals within each filter passband is displayed as a function of the overall filter frequency range. The frequency range of the analyzer is limited by the number of filters and their bandwidth. This arrangement is usually very expensive because of the large numbers of filters required to cover a spectrum, and lacks flexibility in the frequency scale because of the fixed resolution of the filters. It is real time, however, and is better at analyzing low frequencies such as audio and sub-audio range. The bandpass of the filters can be made very narrow for good resolution without having to sacrifice sweep speed as in the swept tuned analyzers. The multichannel analyzer and Fourier Analyzer shown in Figure 1.10 are two widely used real-time analyzers. The Fourier analyzer performs the conversion from time domain to frequency domain by mathematical computation of the Fourier Transform.

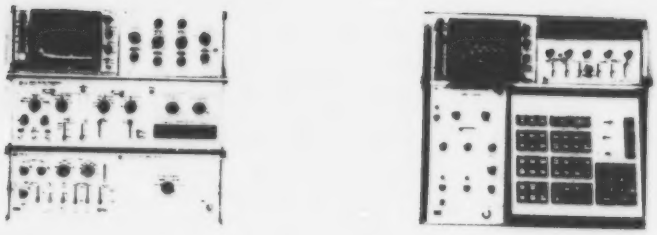


Figure 1.10 A multichannel and Fourier analyzer are shown on the left and right respectively. Both instruments are real-time spectrum analyzers.

The swept-tuned analyzers are usually of the trf (tuned radio frequency) or superheterodyne type. A block diagram of a trf analyzer is shown in Figure 1.11. A trf analyzer consists of a bandpass filter whose center frequency is tunable over a desired frequency range, a detector to produce vertical deflection on a CRT, and a horizontal scan generator used to synchronize the tuned frequency to the CRT horizontal deflection. It is a simple, inexpensive analyzer with wide frequency coverage, but lacks resolution and sensitivity. Because trf analyzers have a swept filter they are limited in sweep width depending on the frequency range (usually one decade or less). The resolution is determined by the filter bandwidth, and, since tunable filters don't usually have constant bandwidth, is dependent on frequency.

The trf analyzer is relatively inexpensive and is often used for microwave applications due to the availability of broadband tuned filters. However, the use of tuned analyzers eliminates the real-time aspect of the display, and sweep rates (MHz/sec) must be consistent with the charge time of the tunable filter.

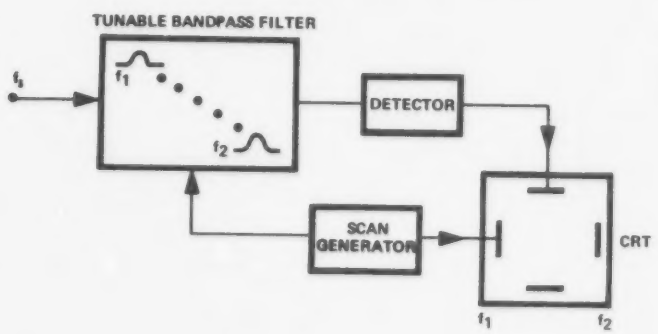


Figure 1.11 Block diagram of a swept trf spectrum analyzer. The frequency spectrum is sampled using a tuned bandpass filter.

The most common type of spectrum analyzer differs from the trf spectrum analyzers in that the spectrum is swept through a fixed bandpass filter instead of sweeping the filter through the spectrum. The block diagram of a swept superheterodyne spectrum analyzer is shown in Figure 1.12. The analyzer is basically a narrowband receiver

which is electronically tuned in frequency by applying a saw-tooth voltage to the frequency control element of a voltage tuned local oscillator. This same saw-tooth voltage is simultaneously applied to the horizontal deflection plates of the CRT. The output from the receiver is synchronously applied to the vertical deflection plates of the CRT and a plot of amplitude versus frequency is displayed.

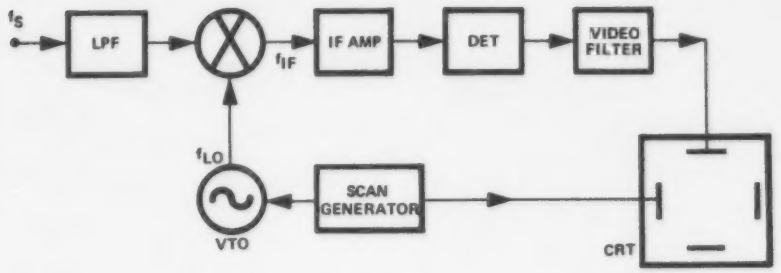


Figure 1.12 Block diagram of a swept superheterodyne spectrum analyzer. The input signal is mixed with a tuned LO frequency to produce a fixed IF which can be detected and displayed.

The analyzer is tuned through its frequency range by varying the voltage on the LO (local oscillator). The LO frequency is mixed with the input signal to produce an IF (intermediate frequency). When the frequency difference between the input signal and the LO frequency is equal to the IF frequency, then there is a response on the analyzer.
If $f_s < f_{LO}$
then

$$f_s = f_{LO} - f_{IF}$$

where

f_s = input signal frequency
f_{LO} = local oscillator frequency
f_{IF} = intermediate frequency

For example, if the first IF is 200 MHz, and the LO tunes from 200-310 MHz, the analyzer would have a 0-110 MHz tuning range. An input signal at 50 MHz would mix with an LO frequency of 250 MHz to produce the 200 MHz IF, and a response would appear on the display.

This is the basic tuning equation used to determine the frequency range of the analyzer. This frequency range can be extended by mixing the input signal with the harmonics of the LO frequency. Harmonic mixing is discussed in the next chapter.

The advantages of the superheterodyne technique are considerable. It obtains high sensitivity through the use of IF amplifiers, and many decades in frequency can be tuned. Also, the resolution can be varied by changing the bandwidth of the IF filters. However, the superheterodyne analyzer is not real-time, and, once again, sweep rates must be consistent with the IF filter charge time.

The superheterodyne approach is the most flexible, and this is what will be discussed in this note.

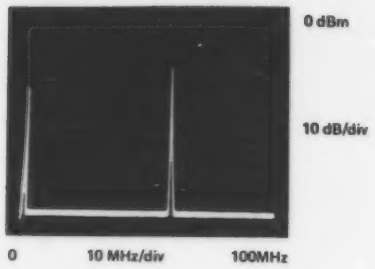


Figure 1.13 Display of a CW signal

Here is a spectrum analyzer display of a CW signal. The signal can be measured from the display.

The response at the left edge of the CRT is sometimes called the "zero frequency indicator" or local oscillator feedthrough. It occurs when the analyzer is tuned to zero frequency, and the local oscillator passes directly through IF creating a response on the CRT even when no input signal is present. (For zero frequency tuning, $F_{LO} = F_{IF}$). This effectively limits the lower tuning limit.

To accurately display the frequency and amplitude of a signal on a spectrum analyzer, the analyzer itself must be properly calibrated. A spectrum analyzer properly designed for accurate frequency and amplitude measurements will satisfy these requirements.

General:

1. Flat frequency response (amplitude is independent of frequency)
2. All functions should be calibrated

Frequency:

1. Wide tuning range
2. Wide frequency display range
3. Stability
4. Resolution
5. Signal identification

Amplitude:

1. High sensitivity
2. Low internal distortion
3. Linear and Logarithmic display modes (voltage and dB)
4. Absolute measurement of amplitude

Modern spectrum analyzers are calibrated in both frequency and amplitude for relative and absolute measurements. The frequency calibration is usually set by the tuning and scale factor controls. The frequency scale can be scanned in three different modes—full, per division, and zero scan. The full scan mode is used to locate signals because the widest frequency ranges are displayed in this mode. Sometimes an inverted marker below the baseline, as shown in Figure 1.14, is used to track the frequency dial on the front panel. When the marker is set under a signal, the frequency dial indicates the signal frequency.

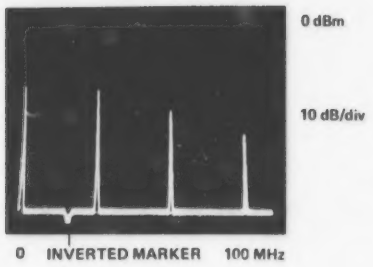


Figure 1.14 An inverted marker is used to indicate the frequency that the analyzer is tuned to. The marker is only present in the full scan mode.

The per division mode is used to zoom-in on a particular signal. In per division, the center frequency of the display is set by the Tuning control and the scale factor is set by the Frequency Span or Scan Width control. The signal in Figure 1.15 was picked out by the inverted marker and zoomed-in on.

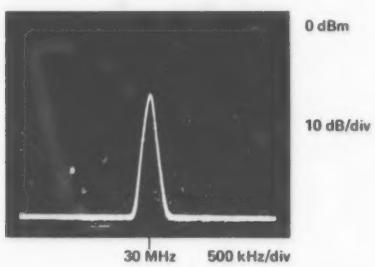


Figure 1.15 This signal was picked out with the inverted marker and zoomed-in on using the per-division scan mode.

In the zero scan mode, the analyzer acts as a fixed-tuned receiver with selectable bandwidths for recovering modulating signals or real-time monitoring of a single signal. AM or FM broadcasts can be heard by plugging headphones into the vertical output on the spectrum analyzer since, in this mode, the analyzer displays amplitude variations versus time at a single frequency. There usually is a built-in envelope detector for recovering AM. FM can be recovered by using the slope of the IF filter as a frequency discriminator. A time domain view of a modulating signal using zero scan is shown in Figure 1.16.

Absolute frequency measurements are usually made from the spectrum analyzer tuning dial.

Relative frequency measurements require a linear frequency scan. By measuring the relative separation of two signals on the display, the frequency difference can be

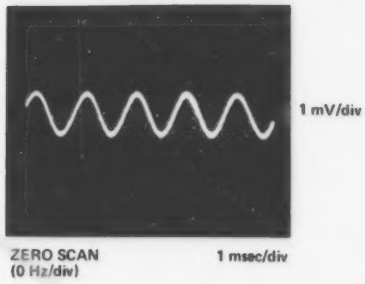


Figure 1.16 This is the modulating wave from an AM signal. The analyzer displays amplitude versus time of the tuned frequency in the zero scan mode.

determined. The linear scan of the spectrum analyzer also means an HP 8406A Frequency Comb Generator can be used to make more accurate absolute frequency measurements. By measuring on the analyzer's CRT display the frequency separation between a known harmonic from the Frequency Comb Generator and an unknown input signal, the frequency of the input signal can be determined. If the analyzer were not sweeping linearly, this would not be possible.

It is important that the spectrum analyzer be more stable than the signals being measured. The stability of the analyzer depends on the frequency stability of its local oscillators. Stability is usually characterized as either short term or long term. Residual FM is a measure of the short term stability which is usually specified in Hz peak-to-peak. Short term stability is also characterized by noise sidebands which are a measure of the analyzer's spectral purity. Noise sidebands are specified in terms of dB down and Hz away from a carrier in a specific bandwidth. An example of noise sidebands and residual FM is shown in Figure 1.17. Long term stability is characterized by the frequency drift of the analyzer's LO's. Frequency drift is a measure of how much the frequency changes during a specified time (i.e., Hz/min. or Hz/hr).

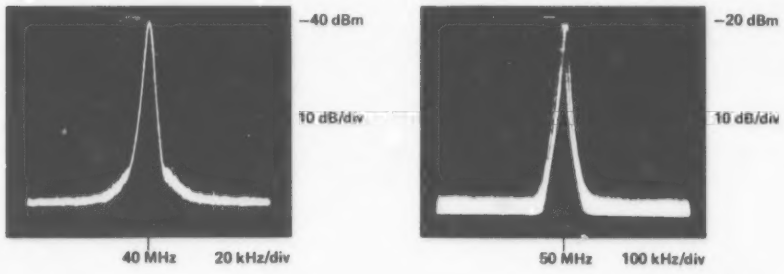


Figure 1.17 A signal with noise sidebands indicating poor spectral purity is shown at left. The residual FM of an oscillator is shown at the right.

Both short term and long term stability can be improved by phase locking the tuned LO to a tooth of a crystal generated frequency comb. The stability of the analyzer is then basically that of the reference crystal oscillator.

Phase locking (or stabilization) should occur automatically whenever a narrow frequency scan is selected. When the tuned local oscillator locks to the crystal reference, some display shift may result due to the pulling of the LO to the lock frequency. If there were no compensation for this, the signal could disappear from the display. In HP analyzers, this shift is compensated for, and no jumping in the display results.

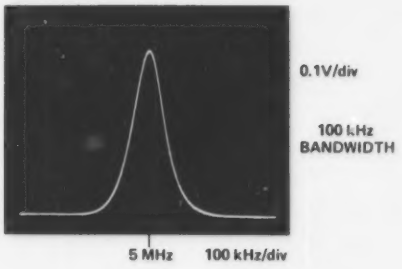


Figure 1.18 As filter is tuned by CW signal, its bandpass shape is traced out on the display.

Before the frequency of a signal can be measured on a spectrum analyzer it must first be resolved. Resolving a signal means distinguishing it from its nearest neighbors. The resolution of the spectrum analyzer is limited by its narrowest IF bandwidth. For example, if the narrowest bandwidth is 1 kHz then the nearest any two signals can be and still be resolved is 1 kHz. This is because the analyzer traces out its own IF bandpass shape as it sweeps through a CW signal.

Since the resolution of the analyzer is limited by bandwidth, it seems that by reducing the IF bandwidth indefinitely, infinite resolution will be achieved. The fallacy here is that the usable IF bandwidth is limited by the stability (residual FM) of the analyzer. If the internal frequency deviation of the analyzer is 1 kHz, then the narrowest bandwidth that can be used to distinguish a single input signal is 1 kHz. Any narrower IF filter will result in more than one response or an intermittent response for a single input frequency as shown in Figure 1.19. A practical limitation exists on the IF bandwidth, as well, since narrow filters have long time constants and would require excessive scan time.

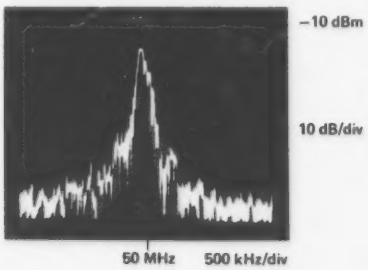


Figure 1.19 Jitter on a signal which is greater than the IF bandwidth.

The resolution of a spectrum analyzer is determined by its IF bandwidth. The IF bandwidth is usually the 3 dB bandwidth of the IF filter. The ratio of the 60 dB bandwidth (in Hz) to the 3 dB bandwidth (in Hz) is known as the shape factor of the filter. The smaller the shape factor, the greater is the analyzer's capability to resolve closely spaced signals of unequal amplitude. If the shape factor of a filter is 15:1, then two signals whose amplitude's differ by 60 dB must differ in frequency by 7.5 times the IF bandwidth before they can be distinguished separately. Otherwise, they will appear as one signal on the spectrum analyzer display. Figure 1.20 shows the bandwidth and shape factor of a typical Gaussian filter.

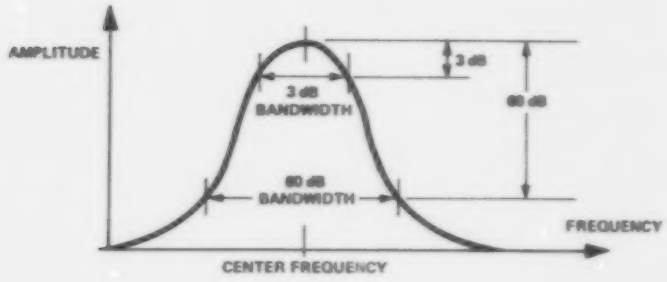


Figure 1.20 Typical Gaussian filter. Signals of equal amplitudes can just be resolved when they are separated by the 3 dB bandwidth. Unequal signals can be resolved if they are separated by greater than half the bandwidth at the amplitude difference between them.

There is a practical limitation on shape factor. The number of poles used in the IF filters will normally determine the shape factor of a synchronously tuned filter. Synchronously tuned (or Gaussian) filters are normally used because of their phase linearity. Shape factor could be improved through the use of stagger-tuned (or square topped) filters. However, such filters have phase discontinuities at their band edges, and, therefore, a ringing is produced when signals are rapidly swept through them as in a spectrum analyzer.

Sometimes IF filter shape factor is specified as the ratio of the 60 dB bandwidth to the 6 dB bandwidth, or the ratio of the 40 dB bandwidth to the 3 dB bandwidth. This can cause difficulty when comparing filters. For example, a 20:1 shape factor measured 60 dB/3 dB is roughly equivalent to a 10:1 shape factor measured 60 dB/6 dB. Even though the shape factor is smaller when specified as the ratio of 60 dB/6 dB, the resolving capability is the same. Therefore, the shape factor is useful as a means of determining filter sharpness only when the dB bandwidths used to determine shape factor are the same for the filters being compared.

The ability of a spectrum analyzer to resolve closely spaced signals of unequal amplitude is not a function of the IF filter shape factor only. Noise sidebands can also reduce the resolution. They appear above the skirt of the IF filter and reduce the offband rejection of the filter. This limits the resolution when measuring signals of unequal amplitude. Noise sidebands can be seen in Figure 1.21.

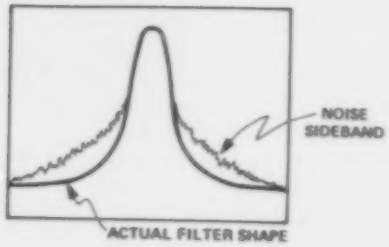


Figure 1.21 Noise sidebands can limit resolution.

When a spectrum analyzer can make both absolute and relative power level measurements, it is said to be absolute amplitude calibrated. To be absolute amplitude calibrated, the analyzer must satisfy these requirements:

1. The input attenuator must be flat to maintain the overall frequency response of the system.
2. The input mixer must be flat or gain compensated over the frequency ranges of the input and LO.
3. The IF attenuator must be accurate for proper amplitude display.
4. The log/linear amplifier must be extremely accurate.
5. The sweep times must be slow enough to allow the IF and video filters to respond fully, or an uncalibrated situation will result.
6. Uncalibrated situations should be indicated by an uncal warning light, or avoided by automatic adjustment of the sweep time for any setting of the video or IF bandwidth or frequency sweep width (See Figure 1.22).
7. Must indicate the absolute signal level represented by some point on the CRT for any control settings, and an amplitude internal reference must be supplied.

Figure 1.22 shows the effects of scanning too fast. When the scan time gets too fast for amplitude calibration, the displayed amplitude decreases and the apparent bandwidth increases. Consequently, frequency resolution gets worse.

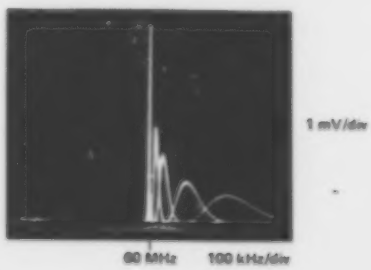


Figure 1.22 When scan time gets shorter and shorter, displayed amplitude gets less and less, and apparent bandwidth gets wider and wider.

Sensitivity is a measure of the analyzer's ability to detect small signals. The maximum sensitivity of an analyzer is limited by its internally generated noise. This noise is basically of two types: thermal (or Johnson) and nonthermal noise. Thermal noise power can be expressed as: $P_N = kTB$

where: P_N = Noise power in watts
k = Boltzmann's Constant (1.38×10^{-23} joule/°K)
T = absolute temperature, °K
B = bandwidth of system in hertz

As seen from this equation, the noise level is directly proportional to bandwidth. Therefore, a decade decrease in bandwidth results in a 10 dB decrease in noise level and consequently 10 dB better sensitivity.

Nonthermal noise accounts for all noise produced within the analyzer that is not temperature dependent. Spurious emissions due to nonlinearities of active elements, impedance mismatch, etc. are sources of nonthermal noise. A figure of merit, ... noise figure, is usually assigned to this nonthermal noise which when added to the thermal noise gives the total noise of the analyzer system. This system noise which is measured on the CRT, determines the maximum sensitivity of the spectrum analyzer. Because noise level changes with bandwidth, it is important, when comparing the sensitivity of two analyzers, to compare sensitivity specifications for equal bandwidths.

A spectrum analyzer sweeps over a wide frequency range, but is really a narrow band instrument. All of the signals that appear in the frequency range of the analyzer are converted to a single IF frequency which must pass through an IF filter; the detector sees only this noise at any time. Therefore, the noise displayed on the analyzer is only that which is contained in the IF passband. When measuring discrete signals, maximum sensitivity is obtained by using the narrowest IF bandwidth.[1]

Measuring small signals can be difficult when they are approximately the same amplitude as the average internal noise level of the analyzer. To facilitate the measurement, it is best to use some degree of video filtering which is usually adjustable from the front panel of the analyzer. A video filter is a post-detection low pass filter which averages the internal noise of the analyzer. When the noise is averaged, the input signal is easily seen. The effects of video filtering are shown in Figure 1.23.

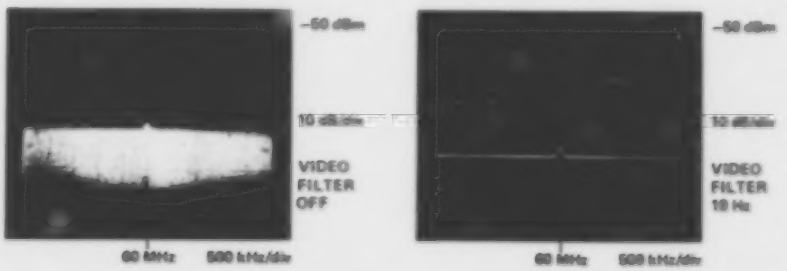


Figure 1.23 How video filter averages noise (right photo) for a better signal-to-noise ratio. No video filtering is used in the left photo.

[1] This is not true, however, for impulse signals such as phase coherent noise. The widest bandwidth gives maximum sensitivity for impulse signals. When measuring random signals such as random or white noise, sensitivity is independent of bandwidth because random input noise varies with bandwidth the same as internally generated noise. See AN 150-4.

Specifying sensitivity on a spectrum analyzer is somewhat arbitrary. One way of specifying sensitivity is to define it as the signal level when:

$$\text{signal power} = \text{average noise power}$$

This expression can be rewritten as:

$$\frac{S + N}{N} = 2$$

Where:

S = signal power
N = average noise power

The analyzer always measures signal plus noise. Therefore, when the input signal is equal to the internal noise level, the signal will appear 3 dB above the noise as in Figure 1.24. When the signal power is added to the average noise power, the power level on the CRT is doubled (increased by 3 dB) because the signal power = average noise power. This is the definition of sensitivity used in describing HP spectrum analyzers. Since a 3 dB difference between the signal level and the average noise level is discernible, it is possible to relate this definition to minimum discernible signal.

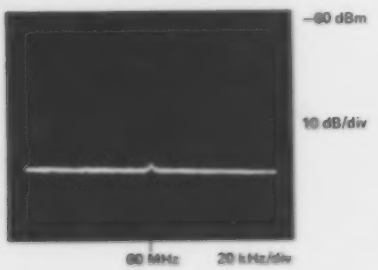


Figure 1.24 When signal power equals average noise power, the signal will appear 3 dB above the average noise level.

Figure 1.25 illustrates a typical range of signal levels that can be applied to the input of a spectrum analyzer with no input attenuation, and the analyzer's reaction to these signal levels.

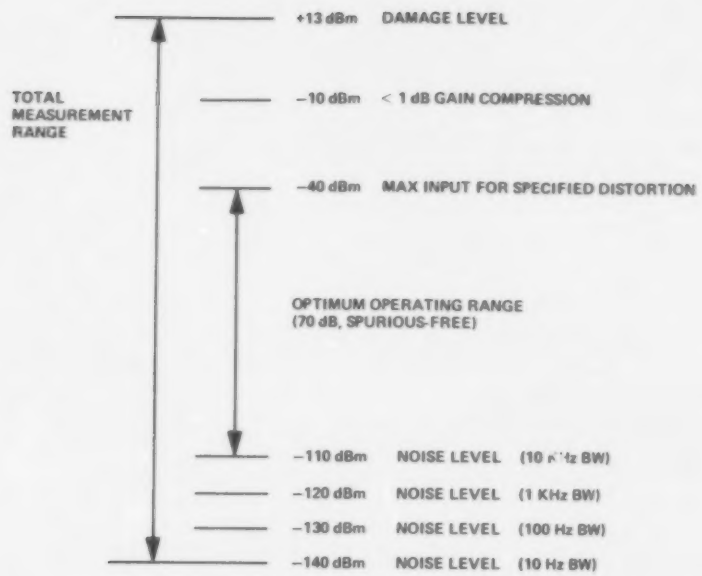

+13 dBm DAMAGE LEVEL
TOTAL MEASUREMENT RANGE
−10 dBm < 1 dB GAIN COMPRESSION
−40 dBm MAX INPUT FOR SPECIFIED DISTORTION
OPTIMUM OPERATING RANGE (70 dB, SPURIOUS-FREE)
−110 dBm NOISE LEVEL (10 KHz BW)
−120 dBm NOISE LEVEL (1 KHz BW)
−130 dBm NOISE LEVEL (100 Hz BW)
−140 dBm NOISE LEVEL (10 Hz BW)

Figure 1.25 Typical spectrum analyzer display range.

The maximum input level to the spectrum analyzer is the damage level or burn-out level of the input circuit. This is typically +13 dBm for the input mixer and +30 dBm for the input attenuator.

Before reaching the damage level of the analyzer, the analyzer will begin to gain compress the input signal. This gain compression is not considered serious until it reaches 1 dB. The maximum input signal level which will always result in less than 1 dB gain compression is called the linear input level. Above 1 dB gain compression the analyzer is considered to be operating nonlinearly because the signal amplitude displayed on the CRT is not an accurate measure of the input signal level.

Whenever a signal is applied to the input of the analyzer, distortion products are produced within the analyzer itself. These distortion products are usually produced by the non-linear behavior of the input mixer. They are typically 70 dB below the input signal level for signal levels not exceeding −40 dBm at the input of the first mixer. To accommodate larger input signal levels, an attenuator is placed in the input circuit before the first mixer. The largest input signal that can be applied, at each setting of the input attenuator, while maintaining the internally generated distortion products below a certain level, is called the optimum input level of the analyzer. For example, a −20 dBm optimum level setting means that all analyzer distortion products are below −90 dBm on the CRT, i.e. down 70 dB. The signal is attenuated 20 dB before the first mixer because the input to the mixer must not exceed −40 dBm, or the analyzer distortion products may exceed the specified 70 dB range. This 70 dB distortion-free range is called the spurious-free dynamic range of the analyzer. The display dynamic range is defined as the ratio of the largest signal to the smallest signal that can be displayed simultaneously with no analyzer distortion products present.

Dynamic range requires several things, then. The display range must be adequate, no spurious or unidentified response can occur, and the sensitivity must be sufficient to eliminate noise from the displayed amplitude range.

The maximum dynamic range for a spectrum analyzer can be easily determined from its specifications. First check the distortion spec. For example, this might be "all spurious products down 70 dB for −40 dBm at the input mixer." Then, determine that adequate sensitivity exists. For example, 70 dB down from −40 dBm is −110 dBm. This is the level we must be able to detect, and the bandwidth required for this sensitivity must not be too narrow or it will be useless. Last, the display range must be adequate.

Notice that the spurious-free measurement range can be extended by reducing the level at the input mixer. For every 10 dB the signal level is reduced, the spurious products will go down at least 20 dB (a net improvement of 10 dB). The only limitation, then, is sensitivity.

To ensure a maximum dynamic range on the CRT display, check to see that the following requirements are satisfied.

1. The largest input signal does not exceed the optimum input level of the analyzer (typically −40 dBm with 0 dB input attenuation).
2. The peak of the largest input signal rests at the top of the CRT display (reference level).

Frequency Response

The frequency response of an analyzer is the amplitude linearity of the analyzer over its frequency range. If a spectrum analyzer is to display equal amplitudes for input signals of equal amplitude, independent of frequency, then the conversion (power) loss of the input mixer must not depend on frequency. If the voltage from the LO is too large compared to the input signal voltage then the conversion loss of the input mixer is frequency dependent and the frequency response of the system is nonlinear. For accurate amplitude measurements, a spectrum analyzer should be as flat as possible over its frequency range.

Flatness is usually the limiting factor in amplitude accuracy since it's extremely difficult to calibrate out. And, since the primary function of the spectrum analyzer is to compare signal levels at different frequencies, a lack of flatness can seriously limit its usefulness.

CHAPTER 2
EXTENDED FREQUENCY COVERAGE THROUGH HARMONIC MIXING

What Is Harmonic Mixing?

To understand harmonic mixing, it's useful to return to the basic block diagram of a spectrum analyzer input section:

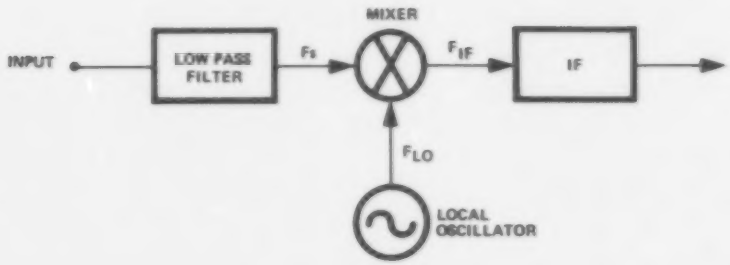


Figure 2.1 Spectrum analyzer Block Diagram.

F_{LO} = Frequency of local oscillator
F_S = Frequency of input signal
F_{IF} = First IF

A response will appear on the analyzer whenever $F_{LO} - F_S = F_{IF}$. This is the basic tuning equation for such a spectrum analyzer. In this case, the first IF and the local oscillator frequencies are *higher* than any input signal to be observed. For example, a 0-1500 MHz spectrum analyzer might be constructed by using a 2 GHz first IF and a 2-3.5 GHz local oscillator.

To extend the frequency coverage of the analyzer, it would be necessary to extend the local oscillator frequency range. However, for coverage into millimeter wave regions an extremely high local oscillator frequency would be required. Clearly, it would be impractical to build, say, a 40-80 GHz oscillator to allow 40 GHz coverage on a spectrum analyzer.

Stability, accuracy, and technology are all limiting factors on high frequency oscillator design.

Well, then, how can frequency be extended? One way would be to remove the low pass filter at the input. In this way the tuning equation could be modified to allow signals higher in frequency than the IF. That is, either equation below would describe the tuning of the analyzer.

$$F_S - F_{LO} = F_{IF}$$
$$F_{LO} - F_S = F_{IF}$$

Or, simplifying:

$$|F_S - F_{LO}| = F_{IF}$$

Then:

$$F_S - F_{LO} = \pm F_{IF}$$

and

$$F_S = F_{LO} \pm F_{IF}$$

Although this more general equation allows extended coverage, there are still limitations due to the available range of local oscillator frequencies.

Consider the effect of creating harmonics of the local oscillator in the input mixer.

This would allow high frequency local oscillator signals while using a lower frequency LO. For example, although a 2-4 GHz LO is used, the 10th harmonic goes from 20 to 40 GHz, thus satisfying the need for a high frequency LO. The tuning equation then becomes:

$$F_S = nF_{LO} \pm F_{IF}$$

This is the general tuning equation for a *harmonic mixing* spectrum analyzer. The input signal can mix with the fundamental or any of the harmonics of the local oscillator to produce the proper IF.

To show how harmonic mixing works, let's choose some typical numbers and graph the results. For the following graphs, a 2 GHz IF and a 2-4 GHz LO will be assumed.

First, let $n = 1$. Since n is the harmonic number of the LO that's being used, this is called *fundamental mixing*. We can plot the LO frequency on the graph horizontal scale, and plot the frequency of the harmonic of the LO on the vertical scale. Then, it's easy to visualize the tuning of the analyzer.

The dotted line represents the harmonic of the LO (on the vertical scale) as the fundamental is tuned over its 2-4 GHz range. For fundamental mixing, of course, the frequencies are the same.

Now, we can draw one curve using the minus sign in the equation and one for the plus sign. These would represent signal frequencies for the 1^- and 1^+ mixing modes respectively. The number indicates the harmonic of the LO which is being used, and the plus or minus sign indicates the sign used in the basic tuning equation.

From the basic tuning equation we can see that the curves will always be separated from the dash line (LO frequency) by the IF (2 GHz). Then, there will be two curves for each harmonic of the LO, separated by twice the IF (or 4 GHz).

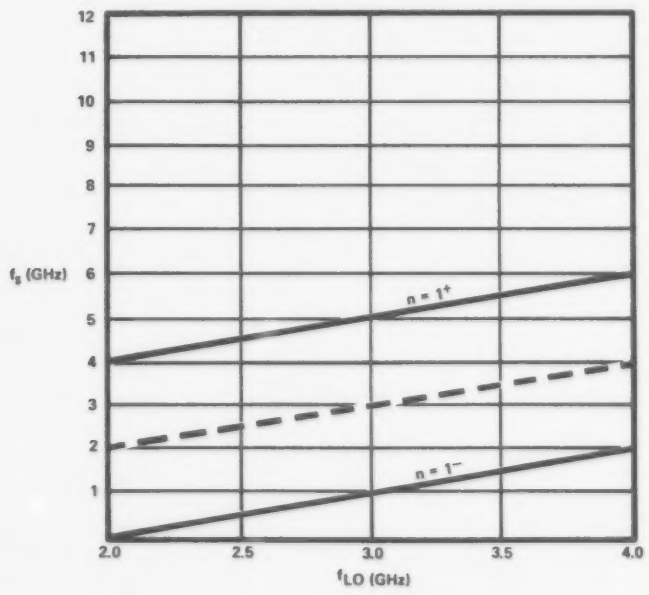


Figure 2.2 Fundamental Mixing.

Now we can readily determine the tuning curves for n = 2, that is, second harmonic mixing. First, we graph the frequency of the second harmonic of the LO as the dashed line. As the LO tunes from 2 to 4 GHz, the second harmonic tunes from 4 to 8 GHz.

The possible tuning frequencies can be represented by two curves, one 2 GHz above the LO and one 2 GHz below. As before, these would be called the 2^+ and 2^- mixing modes. Using second harmonic mixing, then, the analyzer covers the 2 to 10 GHz frequency range.

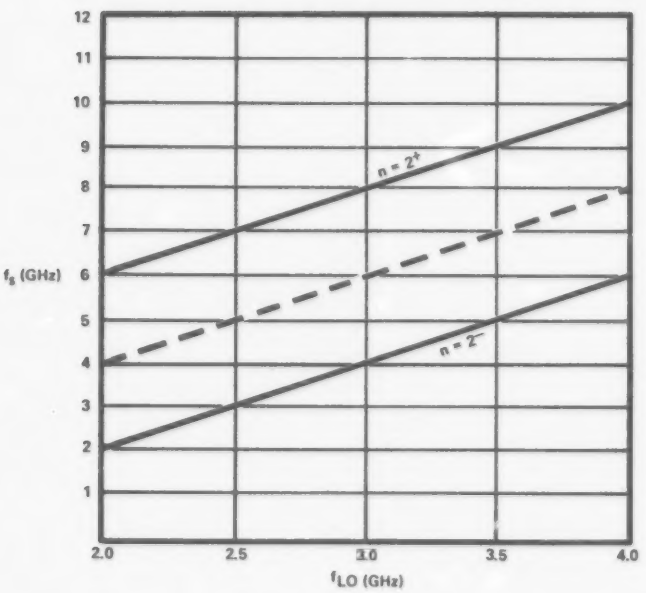


Figure 2.3 Second Harmonic Mixing.

Extending one step further, it's easy to see that the third harmonic of the LO is 6 to 12 GHz, and the tuning curves for third harmonic mixing are as shown.

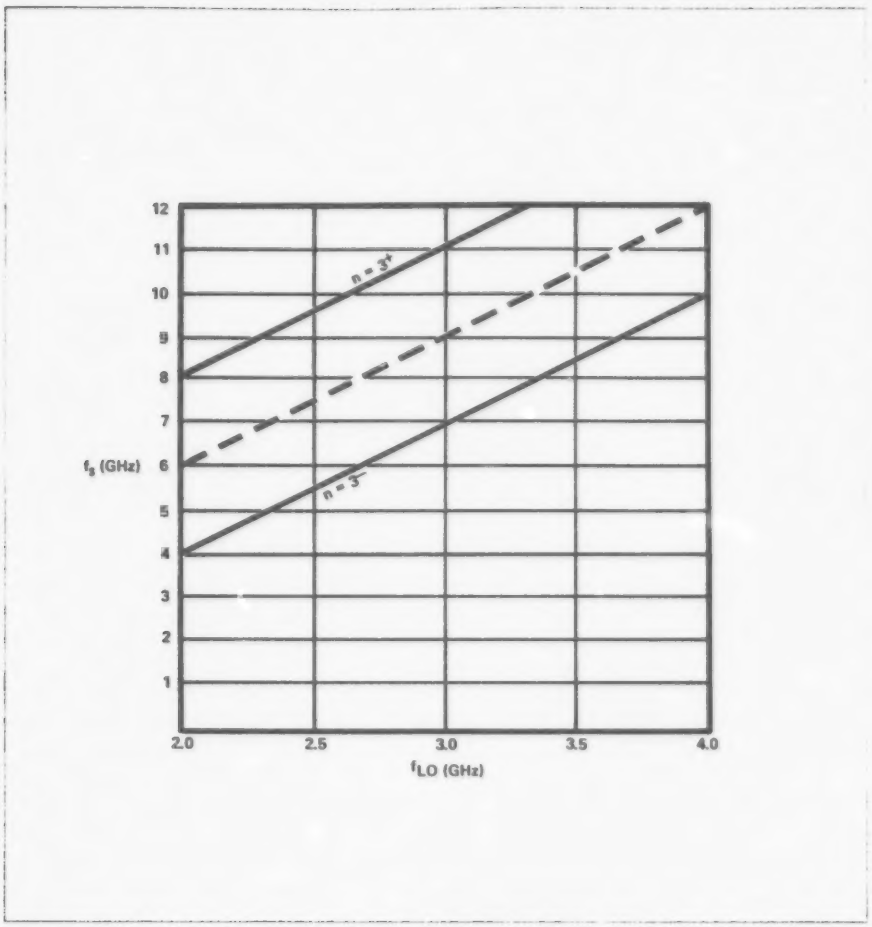


Figure 2.4 Third Harmonic Mixing.

Composite Tuning Curves

Now we can combine all of the tuning curves on a single graph. Notice that by using the first three harmonics of the LO we can measure input signals from 0-12 GHz. In modern analyzers, harmonics up through the tenth harmonic are used to extend the usable frequency range beyond 40 GHz.

The total scan on any frequency band (or harmonic mixing mode) depends on the harmonic of the LO in use. For example, on third harmonic mixing, a total scan of 6 GHz is possible (4 to 10 GHz), while on fundamental mixing, only a 2 GHz scan can be obtained. The frequency scan on any band is equal to the frequency scan of the LO times the harmonic number.

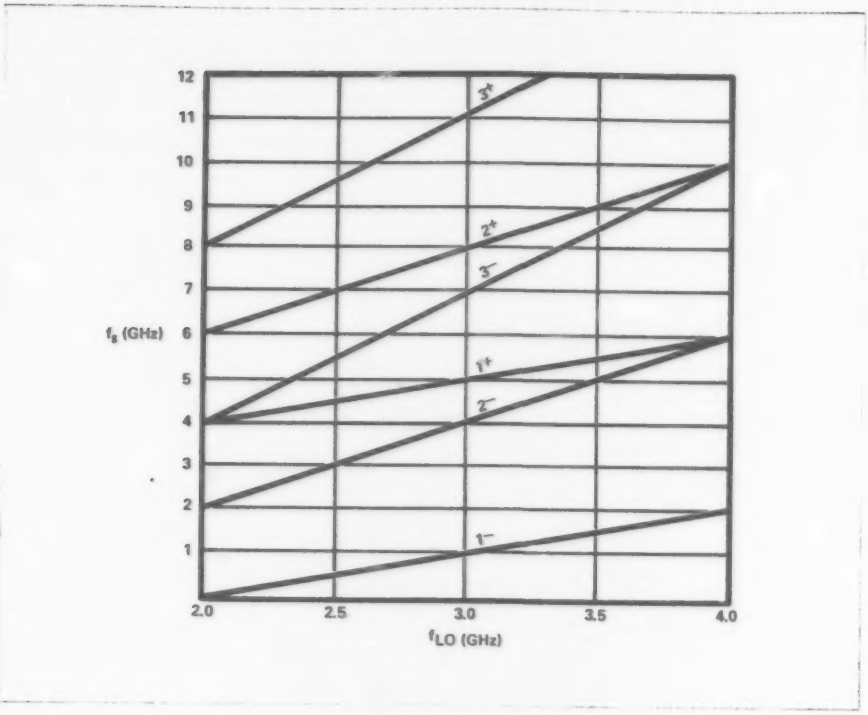


Figure 2.5 Composite Tuning Curves.

The horizontal (frequency) axis of the analyzer CRT is analogous to the local oscillator frequency since the CRT is swept by the same voltage ramp which tunes the LO. That is, on the display, signals which mix with a lower LO frequency will appear to the left of signals which mix with a higher LO frequency. To accurately identify the frequency of a signal on the CRT, then, it is important to know which harmonic mixing mode was used since there are several possible responses for each position on the CRT. In fact, a harmonic mixing analyzer with a "wide open" front end scans simultaneously through all its frequency bands.

Signal Identifier

A *signal identifier* is usually provided to allow identification of the proper mixing mode. The signal identifier shifts a local oscillator (other than the first) by a known amount. Then, the shift of the signal on the display will be proportional to the harmonic number for any mixing mode; the direction of the shift will depend on the plus or minus sign in the tuning equation. In this way, positive identification of any response can be obtained.

Unwanted Responses

Harmonic mixing, as we have seen, allows coverage to higher frequencies. Unfortunately, it also causes some other problems. These, however, can be solved by simple means.

The first of these is *image responses*.

> IMAGE RESPONSES — Response of the analyzer at one LO frequency to input signals of more than one frequency. A pair of image responses exists for each LO frequency and its harmonics.

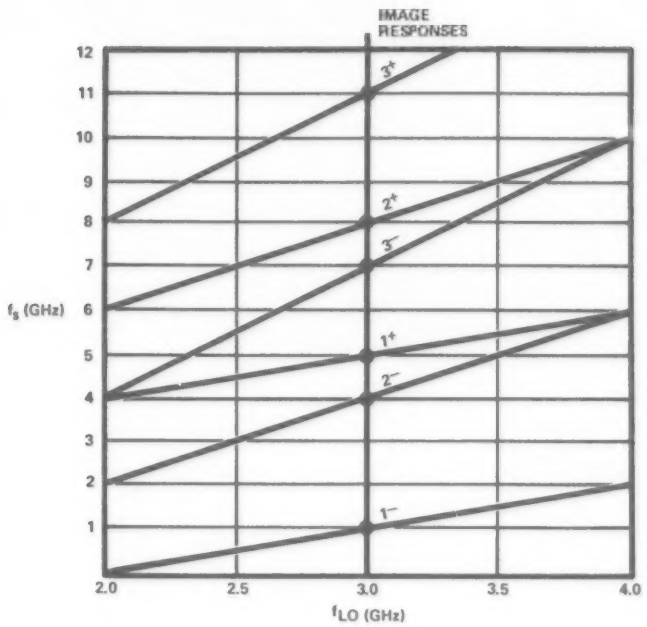


Figure 2.6 Image Responses.

For example, if we have input signals at 1 and 5 GHz, these will both mix with a 3 GHz LO frequency and produce a response at the same place on the CRT. So, there can be several input signals which can appear to be at the same frequency.

The signal identifier would allow proper identification of each response, but it would be better to only have the desired response appear. This can be accomplished with a bandpass filter. In this way, all but the desired signal would be rejected and not appear. In the figure below, a 5 GHz bandpass is used to allow viewing a 5 GHz signal: any 1 GHz present at the input would be rejected.

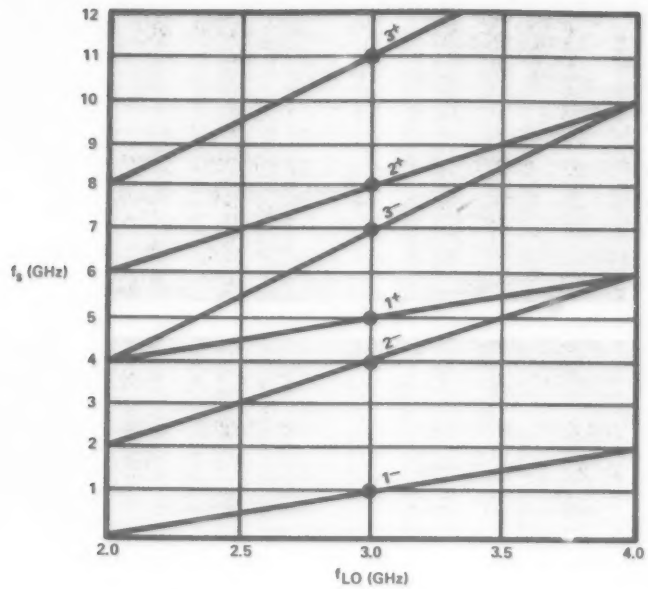


Figure 2.7 Rejection of Image Responses with Bandpass Filter.

MULTIPLE RESPONSES — Responses of the analyzer at more than one LO frequency to an input signal at a single frequency.

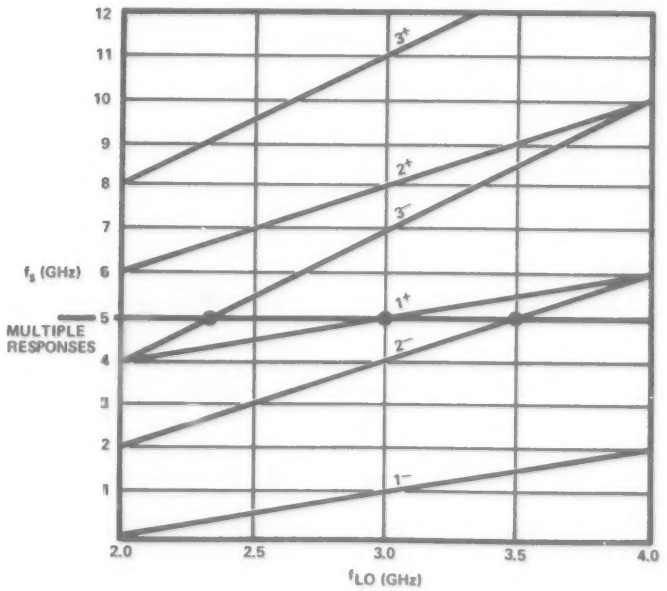


Figure 2.8 Multiple Responses.

This means, for example, that a 5 GHz signal could appear in three places on the CRT corresponding to the three LO frequencies with which it can mix. A fixed bandpass will not cure multiple responses since the desired signal will still be present as the LO is tuned over its range, and all three responses are seen.

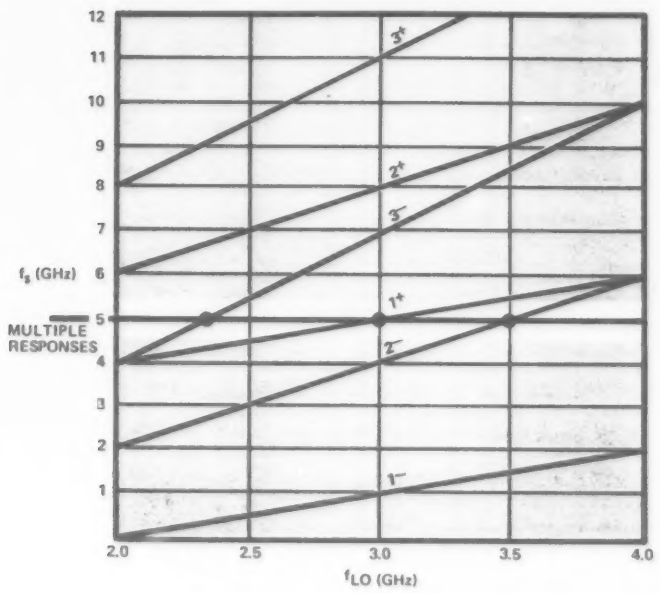


Figure 2.9 Multiple Responses Exist Even with Bandpass Filter.

Suppose a tracking filter could be built, i.e., a bandpass filter which would track the desired tuning curve as the analyzer's LO tunes over its range. Now, the analyzer will only see an input signal when it is tuned to receive that signal. For example, if we wished to view a 5 GHz signal on the 1^+ mixing mode, we could use a filter which tracked this tuning curve. Then, when the LO tunes to 2.33 GHz where we would have a response due to the 3^- mode, the 5 GHz signal is rejected by the filter, and no response appears.

Tuning further, to a 3 GHz LO frequency, the analyzer shows the desired response to the 5 GHz input. The filter passes the 5 GHz signal at this point.

As the analyzer is tuned to the 3.5 GHz LO frequency, the 5 GHz input is rejected, and no response occurs. Thus, a tracking filter solves the problem of multiple responses.

This tracking filter is called a *tracking preselector*. Normally, this is an automatic device which tracks the desired tuning curve when the appropriate frequency band is selected.

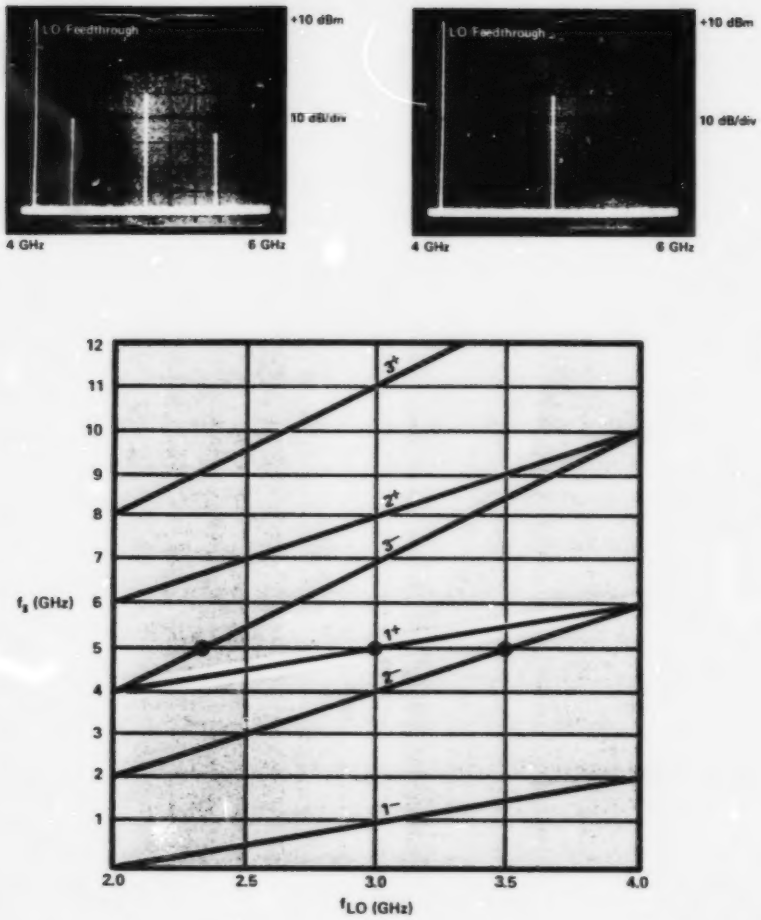


Figure 2.10 Rejection of Multiple Responses with Tracking Filter.

The preselector also eliminates any image responses from the display. Note that the preselector is most effective near the middle of any band where the tuning curves are spaced farthest apart.

Also, the use of the preselector means that wide scans over the full LO range can be made easily since all signals appearing on screen are from the selected band. So, for example, on fourth harmonic mixing, you can scan 8 GHz, etc.

Another problem encountered with a spectrum analyzer is spurious responses.

SPURIOUS RESPONSES — Responses of the analyzer to input signals which are created due to non-linear behavior of the spectrum analyzer.

An example of a spurious response is harmonic distortion. If a 4 GHz signal (with no distortion) is used as in input, the input mixer of the spectrum analyzer may generate some second harmonic distortion at 8 GHz. This would appear on the CRT and be a spurious response.

In extreme cases, there might be several high level input signals, and their harmonics plus all sum and difference products can appear on screen.

Although distortion products are usually specified as >70 dB down for some input level, usable dynamic range can be extended by further eliminating spurious responses. This can be done with a preselector.

For example, for two distortion-free signals at 4.5 and 5 GHz, there are 18 possible responses which can appear due to multiple, image, and second and third order distortion products. The 5 GHz signal appears in three places (multiple responses), the second harmonic of 4.5 GHz appears in three places, etc.

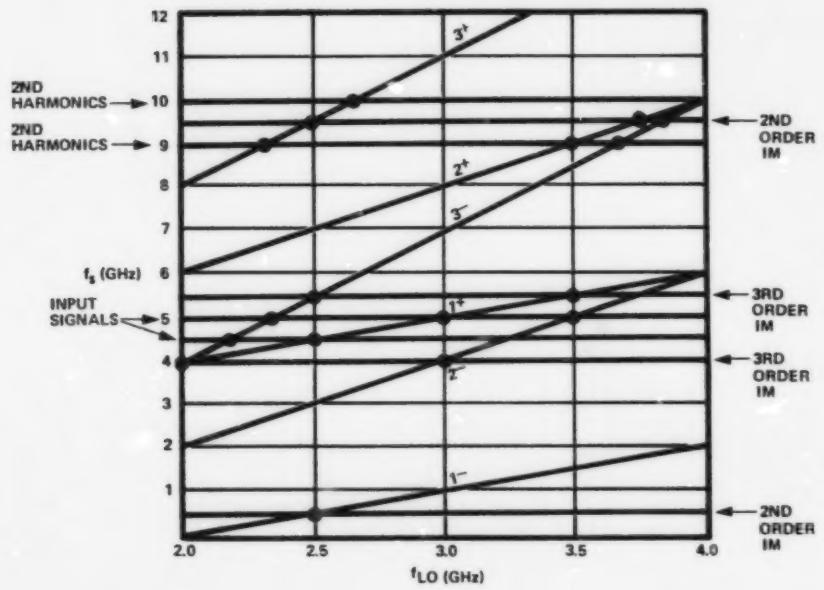
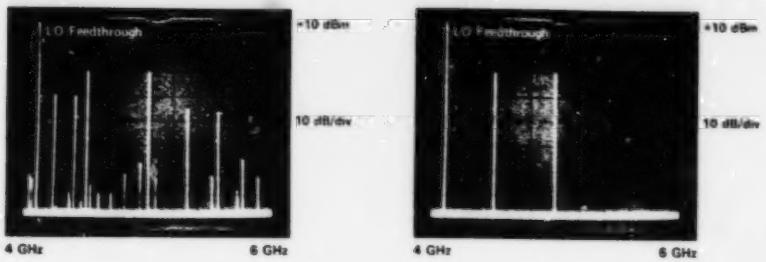


Figure 2.11 Spurious Responses to 4.5 and 5.0 GHz Inputs.

If a preselector is used, however, there are responses to only the two desired input signals. This is because each signal is passed into the mixer only at the precise time the analyzer is tuned to receive it. So, when the analyzer is tuned to the 9 GHz harmonic of 4.5 GHz, the 4.5 GHz is not present at the mixer to generate distortion. Only signals actually present are displayed and only on the selected band. A distortion-free range of greater than 100 dB is achievable with a preselector and spectrum analyzer.



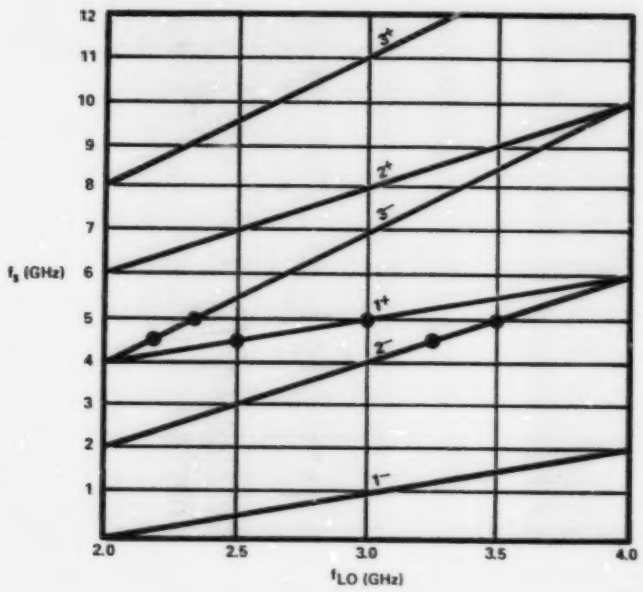


Figure 2.12 Elimination of Spurious Responses with Tracking Filter.

Once again, the input section of a harmonic mixing analyzer will help illustrate a point.

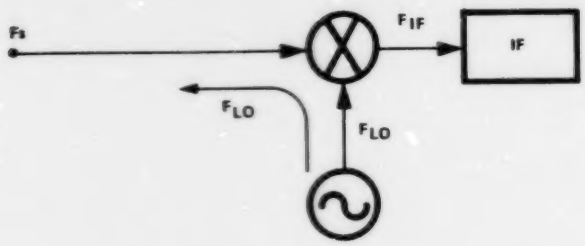


Figure 2.13 LO Emission.

Since the mixer is not typically a balanced mixer, some of the LO signals can be transmitted out the input port at a level of about a milliwatt. This may be a high enough level to damage a sensitive device. On a lower frequency analyzer, the input low pass filter prevents any local oscillator signal from reaching the front panel. A harmonic mixing analyzer, of course, has no such filter. Preselection solves this problem, though, since the preselector is never tuned to the LO frequency; the emission is typically rejected by more than 70 dB.

Returning to the block diagram of the input, consider the effect of an input signal at F_{IF}.

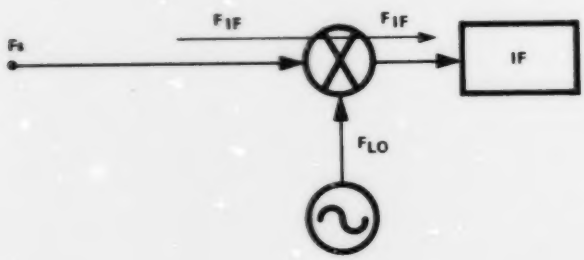


Figure 2.14 IF Feedthrough.

When $F_s = F_{IF}$, the signal can pass straight through the IF section and give a response on the CRT independent of the LO tuning. This would raise the entire baseline of the display to the level of the input signal.

For this reason, an alternate IF is usually provided to allow measurement of a signal near the first IF. For example, the HP 8555A has a 2.05 GHz IF except for two bands which use a 550 MHz IF. In this way, signals near 2.05 GHz may be measured.

If measurements at high frequencies are required while 2.05 is present at the input, a notch filter may be used to eliminate the undesired signal. Note, however, that the tracking preselector would also reject the undesired 2.05 GHz at the input when the analyzer is tuned to any other frequency.

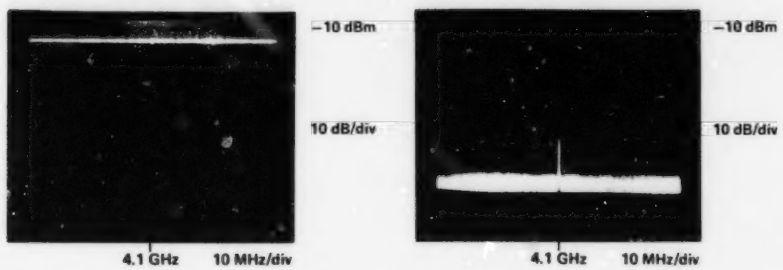


Figure 2.15 Elimination of IF Feedthrough with Preselector.

Using the Signal Identifier With a Preselector

When using a preselector, the signal identifier is not normally required. However, since the tracking filter has only finite rejection. there are cases where signal identification is mandatory to assure a valid measurement.

For example, assume a measurement of spurious outputs from a 5 GHz oscillator is to be made. The display of this signal would look like this if no preselector were used.

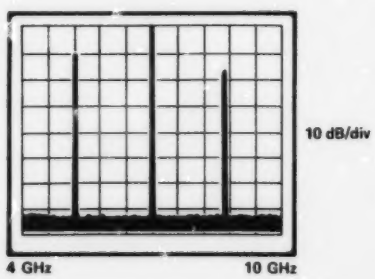


Figure 2.16 Multiple Responses to Strong 5 GHz Signal.

Now, if the preselector is used, we would expect only the desired response to appear. But since typical rejection of the preselectors commonly in use is only about 80 dB, we could see a display similar to this:

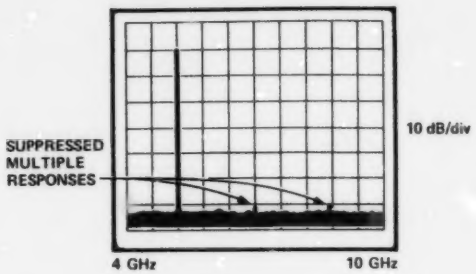


Figure 2.17 Feedthrough of Multiple Responses with Preselector Requires Signal Identifier for Positive Identification.

The only way to be certain that these responses are not spurious outputs would be to use the signal identifier to positively determine the mixing mode. Otherwise, a strong signal will appear as a small signal on each mixing mode and will hinder measurements where wide dynamic range is required.

Tracking preselectors are not normally available for low frequency spectrum analyzers. There are some good reasons for this.

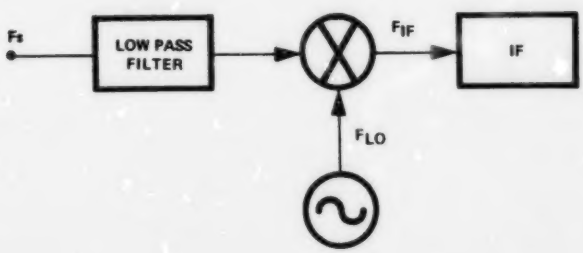


Figure 2.18 Low Frequency Analyzer Using Only 1^- mode.

By reviewing the basic block diagram for a low frequency analyzer, it's obvious that only the 1^- mixing mode is possible. That is, both F_{LO} and F_{IF} are higher than the cut off frequency of the low pass filter. This means there can be no multiple or image responses. Also, IF feedthrough and LO emission are both prevented by the low pass filter.

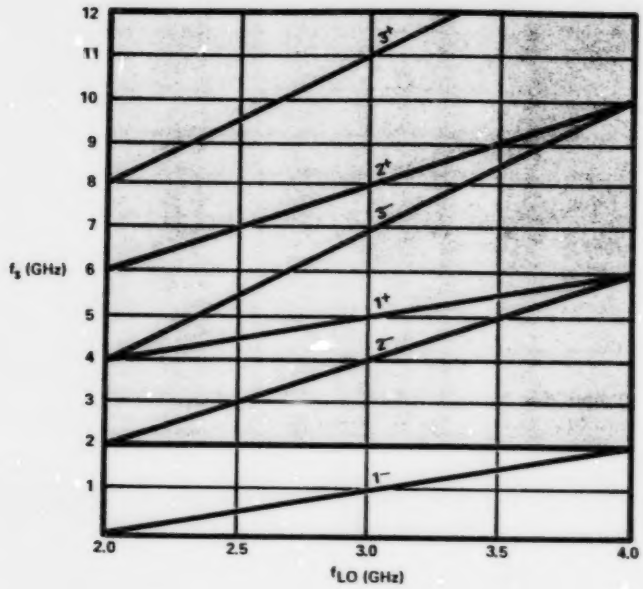


Figure 2.19 Only 1⁻ mode is possible with Low Pass Filter at Input.

Another limitation imposed is the frequency range covered by a low frequency analyzer may extend over several decades, making it extremely difficult to build tunable filters over the same range.

Thus, even though performance of the analyzer could be improved due to better rejection of spurious responses, preselectors are not normally used. However, fixed filters are used in some special applications to obtain the same effect.

Up to now we have discussed the benefits derived from the use of a tracking preselector. Obviously, there must also be some negative points.

Since the filter used must have some insertion loss, there will be a loss in sensitivity of the analyzer. Also, this loss is not constant with frequency so some degradation of overall flatness results.

Flatness can also be degraded due to mismatch between the preselector and the input mixer of the spectrum analyzer since the filter reflects nearly all power outside its passband. To correct this, attenuation is usually used between the preselector and mixer. However, this further degrades sensitivity.

A further reduction in flatness can result if the preselector does not accurately track the spectrum analyzer tuning.

Where maximum sensitivity and flatness are required, it is advantageous to remove the preselector from the circuit. But, for most applications, it is sufficient to remember a few simple rules: use at least 10 dB of input attenuation whenever possible, and check the tracking adjustments of the preselector periodically.

As the spectrum analyzer uses higher harmonics of the LO, less oscillator power is available. This means that the conversion loss of the input mixer is greater for higher harmonics. The gain of the spectrum analyzer is compensated to account for this effect. Thus, it is necessary to identify the proper harmonic mixing mode before making any amplitude measurements. Also, since the gain of the analyzer changes with mixing mode, the displayed noise level will also change; sensitivity is less on higher harmonics.

As the first LO is multiplied in frequency, any instability is also multiplied. For example, if the first LO has 30 Hz residual FM, then on fourth harmonic mixing, the FM would be 30 x 4, or 120 Hz. This effect can be a determining factor in selecting the minimum usable resolution bandwidth for any mixing mode. Excellent LO stability is necessary if high resolution is needed on higher harmonic mixing.

The tracking generator is a special signal source whose RF output frequency tracks (follows) some other signal beyond the tracking generator itself. In conjunction with the spectrum analyzer, the tracking generator produces a signal whose frequency precisely tracks the spectrum analyzer tuning. Because of this feature, the two instruments combine to make a powerful and versatile measurement system. However, before going into the measurement capabilities of the system, look briefly at the simplified block diagram of a spectrum analyzer/tracking generator as shown in Figure 3.1. The spectrum analyzer portion is the same block diagram described in the previous sections.

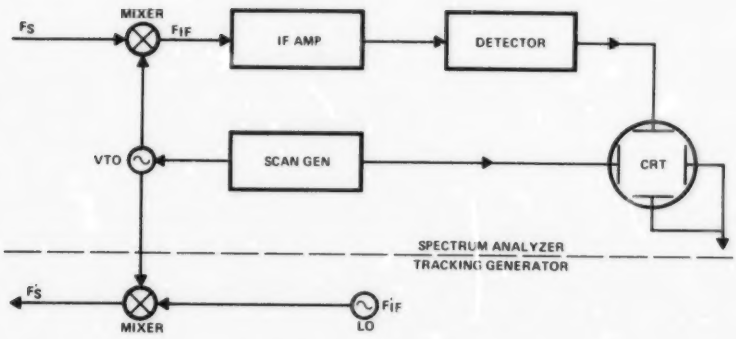


Figure 3.1 Simplified Spectrum Analyzer/Tracking Generator.

The tracking generator has a stable, fixed (F'_{IF}) local oscillator. If we make $F'_{IF} = F_{IF}$ then $F_S = F'_S$ where

$$F_s = F_{vto} - F_{IF} \text{ and } F'_s = F_{vto} - F'_{IF}.$$

Hence, the tracking generator frequency (F'_s) precisely tracks the spectrum analyzer tuning (F_s) since both are effectively tuned by the same VTO. This precision tracking exists in all analyzer scan modes. Thus, in full scan, the tracking generator output is a start-stop sweep, in per division scan the output is a ΔF sweep, and in zero scan the output is simply a CW signal.

The tracking generator signal is generated by synthesizing and mixing two or more oscillators. One oscillator is part of the tracking generator itself, the other oscillators are brought via an interface cable from the spectrum analyzer. Depending on the analyzer, the interface cable carries two or three LO's.

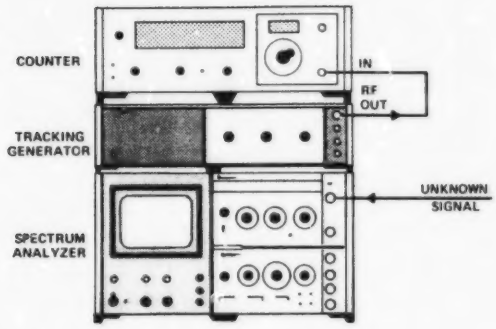


Figure 3.2 Open-Loop Configuration.

The spectrum analyzer/tracking generator system is used in two configurations: open-loop and closed-loop. In the open-loop configuration, unknown external signals are connected to the spectrum analyzer input and the tracking generator output is connected to a counter. This configuration is used for making *selective and sensitive precise measurement of frequency.*

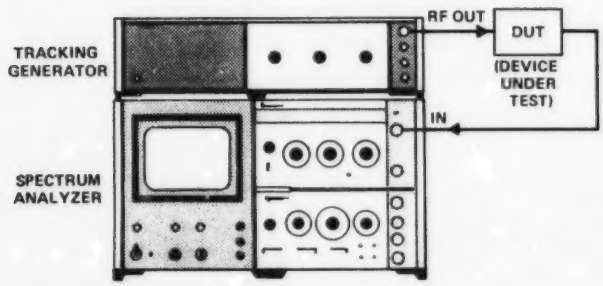


Figure 3.3 Closed-Loop Configuration.

In the closed-loop configuration, the tracking generator signal is fed into the device under test and the output of the device under test is connected tc the analyzer input. This configuration is used for making *magnitude only swept transmission/ reflection measurements;* i.e., insertion loss, return loss, SWR, and reflection coefficient. In the following pages, these two configurations will be discussed in some detail.

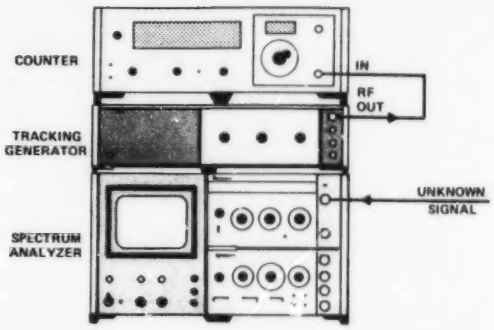


Figure 3.4 Precise Measurement of Frequency.

Figure 3.4 is an open-loop configuration where the spectrum analyzer/tracking generator is used as a highly selective, highly sensitive, precision frequency measurement system. The CRT photo shown in Figure 3.5 is an example of the measurement capability of this system.

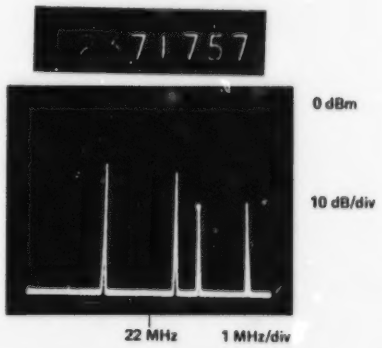


Figure 3.5 This CRT display shows several signals. The smallest signal (—44 dBm) was counted by placing a special marker at its peak. The marker forces a momentary pause in the analyzer scan, the pause allows the counter to trigger and count.

When unknown signals are connected to the analyzer input, they are separated into their frequency components and displayed on the CRT. These signals may be very small and undetectable by a counter or they may be large, but regardless of their level, the tracking generator output is enough to drive the counter. Thus, the frequency of any signal or component can be measured by simply *stopping the scan manually or electronically* at the peak of the displayed signal and counting the tracking generator output frequency as shown in Figure 3.6. This measurement would not have been possible if precision tracking did not exist between the analyzer tuning and the tracking generator frequency.

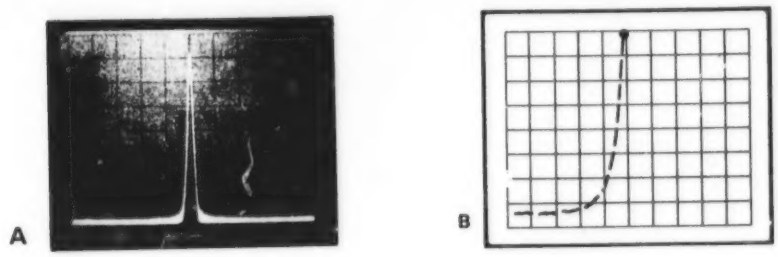


Figure 3.6 Counting Illustration.
A. This is the display of a CW signal.
B. To count the frequency shown in A, stop the scan manually or electronically at the peak of the signal and read the counter display.

The question that should come to mind at this point is, "Why can't we count the unknown signal by connecting it directly to the counter?" A partial answer to this question is yes, we can, but only for spectrally clean, stable, and high level signals. The complete answer will be apparent below when the system sensitivity and selectivity have been considered. But before doing this, let us establish that the indirect counting technique (counting the tracking generator frequency instead of the unknown signal itself) does not diminish the frequency accuracy of the system as a whole.

In the open-loop configuration, frequency accuracy is limited by two factors: (1) the tracking error which exists between the analyzer tuning and the generator output frequency, and (2) the residual FM of the tracking generator output frequency.

Since the tracking generator precisely tracks the analyzer tuning, tracking error is seldom worse than a few parts per million. Thus, the tracking error contribution is minimal.

The residual FM of the tracking generator is made up of the residual FM of the local oscillators in the analyzer and the tracking generator. These oscillators have very low residual FM, due to internal stabilization. Hence, the contribution of the residual FM of the tracking generator signal is also minimal.

Counting the tracking generator frequency instead of the unknown signal itself is potentially highly accurate.

Any signal displayed on the analyzer CRT, from the analyzer burnout to the noise level, can be counted. This simply means that this is a counting system with a sensitivity identical to that of the analyzer.

The significance of the tracking generator in this application is that its output level is sufficient to drive a counter regardless of the level of the unknown signal, and therefore it effectively transfers the analyzer sensitivity to the counter. Furthermore, since the analyzer sensitivity is bandwidth dependent, we can increase sensitivity by narrowing the analyzer's IF bandwidth. Very small signals, on the order of tens of nanovolts (10^{-9}), can be displayed and their frequency counted. By contrast to a stand-alone counter, this sensitivity far exceeds available counter sensitivity and is equivalent to about 60 to 70 dB improvement. Figure 3.7 shows a signal at −110 dBm which was counted with the help of a tracking generator. There's no way to count this signal directly.

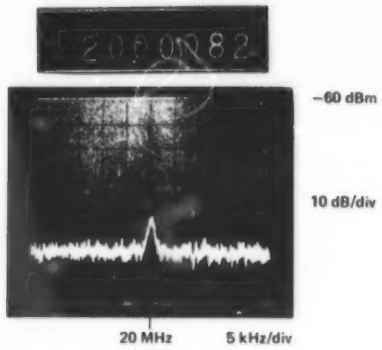


Figure 3.7 This signal is −110 dBm. It was counted using a spectrum analyzer/tracking generator.

The spectrum analyzer has several scan widths and several IF bandwidths, both ranging from very narrow to very broad. Adjusting the scan width controls the portion of the spectrum being scanned and displayed on the CRT; and adjusting the IF bandwidth controls the minimum separation required for resolving two closely spaced signals.

Another facet of interest is that the analyzer is amplitude-selective through its filter skirt. Signals differing in amplitude by as much as 70 dB and separated by some minimum frequency can be resolved and displayed simultaneously.

The spectrum analyzer/tracking generator makes a highly selective frequency measurement system as shown in Figure 3.8. The end limitation to selectivity is what can be resolved on the CRT. Here again, if a signal can be resolved, its frequency can be measured; simply stop the scan manually or electronically at the peak of the desired signal and read the counter display.

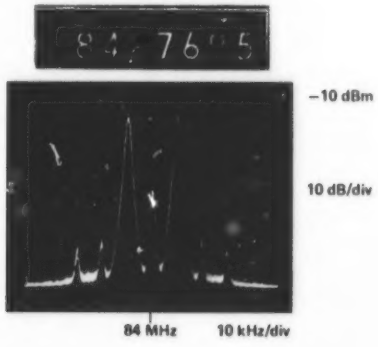


Figure 3.8 This is a suppressed carrier spectrum. The carrier frequency was counted as shown. Notice the selectivity of the spectrum analyzer/tracking generator system.

In summary, the fundamental signal, harmonics, sidebands (including FM and PM signals), and non-random spurious signals can be indirectly counted by adjusting the analyzer scan width and IF bandwidth. In this application, the counter effectively acquires the sensitivity and selectivity of the spectrum analyzer. The conventional counter, by contrast, is triggered by the highest level signal, thus affording little sensitivity and selectivity, if any.

In this configuration, the spectrum analyzer/tracking generator becomes a self-contained, complete (source, detector, and display) swept frequency measurement system. An internal leveling loop in the tracking generator ensures a leveled output over the entire frequency range. The specific swept measurements that can be made with this system are frequency response (amplitude vs. frequency), magnitude only reflection coefficient, and return loss. From return loss or reflection coefficient, the SWR can be calculated. Swept phase and group delay measurements cannot be made with this system; however, it does make some unique contributions not made by other swept systems, such as a sweeper/network analyzer, a sweeper/spectrum analyzer, or a sweeper/detector/oscilloscope.

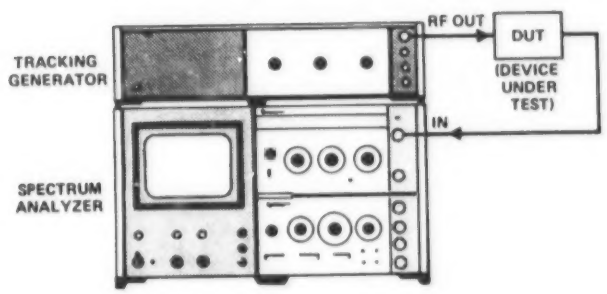


Figure 3.9 Swept Frequency Measurements.

The spectrum analyzer/tracking generator has three attractive features:

1. Large amplitude dynamic range
2. Narrow/wide scan widths
3. Excellent frequency accuracy

Each of these features is discussed separately on the following pages.

The measurement dynamic range of the spectrum analyzer/tracking generator may exceed 120 dB. The key to this large dynamic range is the precision tracking which exists between the analyzer tuning and the generator RF output frequency. This precision tracking permits over-driving the mixer to the 1 dB compression level while keeping the analyzer distortion products off the CRT. Figure 3.10 shows the dynamic range capability of the spectrum analyzer/tracking generator system.

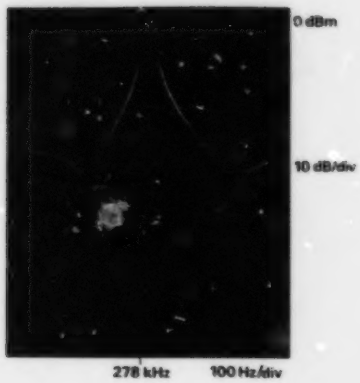


Figure 3.10 This CRT photograph shows the frequency response of a 278 kHz bandpass filter over a range greater than 85 dB.

Precision tracking means at every instant of time the generator fundamental frequency is in the center of the analyzer passband, and all generator harmonics, whether they are generated in the analyzer or are produced in the tracking generator itself, are outside the analyzer passband. Thus, only the tracking generator fundamental frequency is displayed on the analyzer's CRT. Second and third order harmonics and intermodulation products are clearly out of the analyzer tuning and, therefore, they are not seen. Thus, while these distortion products may exist in the measurement set-up, they are completely eliminated from the CRT display.

The 1 dB gain compression level is a point of convenience, but it is nonetheless considered the upper limit of the dynamic range. The lower limit, on the other hand, is dictated by the analyzer sensitivity which, as we know, is bandwidth dependent. The narrowest usable bandwidth in turn is limited by the tracking generator residual FM and any tracking drift between the analyzer tuning and the tracking generator signal.

The measurement dynamic range obtained with most other techniques does not exceed 60 to 80 dB, whether a network analyzer, a spectrum analyzer (with non-synchronous source) or a detector/oscilloscope is used for detection and display. The limitation differs with each display. For the network analyzer, the limitation is noise generated in the analyzer channels; for the spectrum analyzer, it is distortion created in the spectrum analyzer by the sweeper signal (since the sweeper is not synchronously tuned with analyzer), and for the detector/oscilloscope, it is the detector square law operation.

Because of precision tracking, the tracking generator output frequency acquires the same scan capability as the spectrum analyzer. Hence, the analyzer's several calibrated scan widths which range from broadband to extremely narrow band are acquired by the tracking generator. However, it is the tracking generator's inherently low residual FM (<1 Hz below 110 MHz, <200 Hz above) which makes narrow scanning meaningful and usable. Figure 3.11 shows a 200 Hz scan and a 100 MHz scan using the spectrum analyzer/tracking generator system.

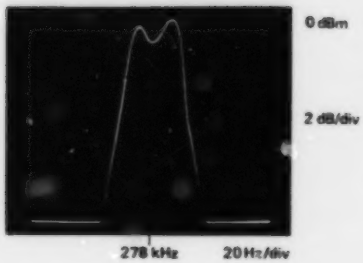


Figure 3.11 Narrow and wide scanwidths of the spectrum analyzer/ tracking generator. The narrow scan width photo shows the passband details of the filter shown in Figure 3.10 on previous page.

The large dynamic range discussed above makes the narrow scan capability particularly significant. Very narrow band, high "Q" devices can be swept frequency tested with excellent amplitude and frequency resolution. The wide scan width capability, on the other hand, makes it possible to view the frequency response over a wide frequency range.

By contrast, the residual FM of most conventional sweepers in this range is a few kHz (3-10 kHz); thus it precludes very narrow band measurements.

In the closed-loop configuration, the CRT displays the frequency response of the device under test. Frequency accuracy in this configuration means the ability to identify and measure the frequency of any point on the CRT display.

The amplitude dynamic range and the scan capability of the spectrum analyzer/ tracking generator make identification of any point on the display quite easy and unambiguous. Thus, we can identify the 3 dB points, 60 dB points, center frequency, etc. The frequency of any point on the display is measured by connecting a counter to the tracking generator output and stopping the scan (manually or electronically) at the point of interest. Figure 3.12 shows a 50 MHz bandpass filter. Its 3 dB and 60 dB bandwidths were counted.

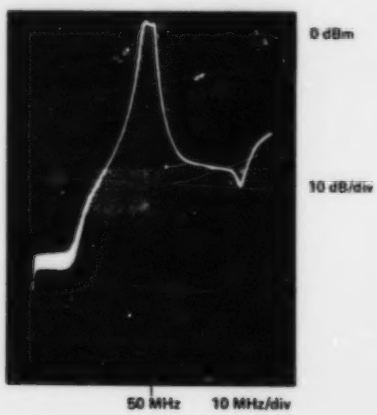


Figure 3.12 This CRT photograph shows the frequency response of a 50 MHz bandpass filter over a range greater than 90 dB.

The accuracy of this measurement is limited by the tracking generator residual FM plus the counter's own accuracy. Excluding the counter contribution, this accuracy ranges from 3 to 200 Hz for Hewlett-Packard spectrum analyzer/tracking generator systems. By comparison, the accuracy obtained from counting most conventional sweepers varies from 3 to 10 kHz. Here again, the limitation is the sweeper residual FM, which is usually several orders of magnitude greater than that of the tracking generator.

It should be pointed out that precision tracking does not affect frequency accuracy in the closed-loop configuration. To see why this is true, let us consider the case where tracking is deliberately degraded. Precision tracking places the tracking generator signal in the center of the IF bandwidth. Thus, when tracking is degraded, the tracking generator frequency shifts from the center of the IF bandwidth and the analyzer response simply decreases in amplitude, and a slight shift in the display results.

The CRT photograph in Figure 3.13 demonstrates this result. Curve A is the frequency response of a bandpass filter and is taken at maximum tracking. Curve B is for the same filter, but tracking has been deliberately degraded. Notice how in curve B the entire display has shifted downward, and that the center frequency, 3 dB points, 60 dB points, etc., are still preserved. This is true because of counting the frequency of the applied stimulus; i.e., the same response must always occur at the same stimulating frequency, even though the display itself may shift horizontally.

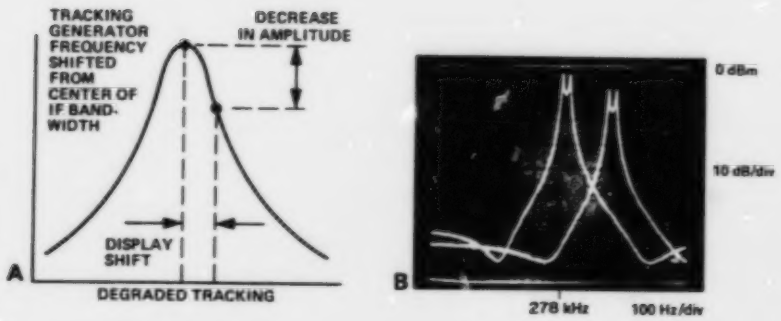


Figure 3.13 Degraded Tracking Effect.
A. The tracking generator frequency shifted from the center of the IF bandwidth.
B. CRT display with maximum and degraded tracking.

Spectrum analysis is defined as the study of energy distribution as a function of frequency. From this study comes valuable information for engineers designing a variety of systems and components; such as communication systems, control systems, radar and navigation systems and components for any of these systems.

SPECTRUM ANALYZER: The spectrum analyzer is an instrument designed to graphically present the energy distribution of a signal as a function of frequency. Typically, the display is a cathode ray tube (CRT) screen which shows amplitude vs. frequency. There are two types of spectrum analyzers; real-time and non-real-time. Non-real-time analyzers are known as scanning analyzers.

> REAL-TIME SPECTRUM ANALYZER: This is a spectrum analyzer which is tuned to the entire spectrum at once, thus it responds to changes in signals as they occur.
>
> NON-REAL-TIME (SCANNING) ANALYZER: This analyzer is only tuned to a single frequency at a given instant in time; so to analyze several signals, it sequentially scans through them one at a time. Because it must wait to tune to a particular frequency, it is not a real-time analyzer. The phenomenon under test must be repetitive, otherwise, it may not be detected. Scanning analyzers are usually the superheterodyne receiver type in which the first local oscillators (LO) or some IF is swept. HP analyzers are generally superheterodyne swept first LO, and all the terms defined below apply to our non-real-time spectrum analyzers.

FREQUENCY RANGE: The range of frequencies to which the analyzer can be tuned.

FREQUENCY ACCURACY: This refers to the accuracy of the analyzer tuning. It is specified as ± X MHz or parts per million of the dial scale or digital panel meter reading.

FREQUENCY RESOLUTION: Resolution is the ability of the analyzer to resolve two real signals present at its input. Closely spaced signals are more difficult to resolve than widely spaced signals. Several factors affect resolution, the most important of these is the final IF bandwidth and the shape factor.

RESOLUTION BANDWIDTH: This is the 3 dB bandwidth of the analyzer final IF stage. It is called the resolution bandwidth because two closely spaced, equal amplitude signals are just resolved if they are separated by an amount equal to the analyzer 3 dB bandwidth. For example, a final IF bandwidth of 100 Hz just resolves two equal amplitude signals 100 Hz apart. However, if the two signals are less than 100 Hz apart, they will be within the IF bandwidth at the same time and, therefore, will appear as one signal.

OPTIMUM RESOLUTION BANDWIDTH: This is the bandwidth which provides the most convenient display commensurate with scan width and reasonable sweep time.

BANDWIDTH SHAPE FACTOR: Shape factor is a measure of how wide the final IF filter is below the 3 dB points. This factor shows the analyzer's capability to resolve closely spaced signals of unequal amplitudes.

Shape factor is the ratio of

$$\frac{\text{Bandwidth 60 dB down (in Hz)}}{\text{Bandwidth at 3 dB (in Hz)}}$$

The smaller this ratio the sharper is the filter and the more selective it is.

SPAN, SCAN: They are identical, interchangeable terms. they refer to the calibration of the horizontal axis of the analyzer. The horizontal axis has 10 divisions and units are in Hz, KHz or MHz.

SCAN WIDTH OR FREQUENCY SPAN: This refers to the portion of the frequency range which is displayed on the CRT. There are three Scan (Frequency Span) modes; Full, per division, and Zero. Per division is subdivided into three types: center, start and 0-10F.

FULL SCAN: In this mode, the horizontal axis of the CRT display corresponds to the full frequency range of the analyzer. The left edge graticule line corresponds to the analyzer lower end frequency while the right edge graticule line corresponds to the upper end frequency. Internally, the analyzer first LO is sweeping across its full frequency range.

PER DIVISION SCAN

A. CENTER SCAN: In this mode, the horizontal axis is symmetrical about the center frequency which is set by the analyzer tuning control. The total scan width is equal to 10 x scan width/division setting. Internally, the analyzer first LO sweeps symmetrically about the frequency selected by the tuning control.

B. START SCAN: In this mode, the horizontal axis Start frequency (instead of the Center frequency) is set by the tuning control. The total frequency span displayed is still 10 x frequency span/division setting. Internally, this mode is similar to a Start/Stop sweep mode in Sweep oscillators, i.e., the analyzer first LO sweeps a range of frequencies starting at the frequency set by the tuning control and stopping at the frequency set by the frequency span control.

C. 0-10F SCAN: In this mode, the start frequency is always 0, the end frequency is equal to 10F where F = the scan width/division setting. Internally, the analyzer LO sweeps a range of frequencies, the low end frequency is preset while the high end frequency is set by scan width control.

ZERO SCAN: In this mode, the horizontal axis is calibrated in real time at a single frequency. The analyzer is CW tuned in this mode, (i.e., O Hz/division) thus time variations of the signal amplitude are displayed on the CRT and the analyzer becomes a tunable, variable bandwidth receiver.

SCAN (FREQUENCY SPAN) LINEARITY: This refers to the accuracy of the horizontal axis of the display, i.e., the frequency error between two points on the CRT.

FREQUENCY STABILITY: This refers to the stability of the analyzer as a measurement system. Since the analyzer must be more stable than the signals it measures, frequency stability considerations become particularly important. Usually, the analyzer frequency stability is equal to the sum of the frequency stabilities of its local oscillators. Two measures of frequency stability are used: short term and long term. Residual FM and noise sidebands are used to measure short term stability while drift is used to measure long term stability.

RESIDUAL FM: Residual FM is a short term measure of the analyzer jitter or aberrations. It is usually measured in some bandwidth and is specified as so many Hz RMS, peak, peak-to-peak or average in one second interval. The analyzer's narrowest bandwidth and scan width are limited by the residual FM.

NOISE SIDEBANDS: Noise sidebands are a measure of the analyzer spectral purity, i.e., how spectrally clean the analyzer local oscillators are. This specification is significant because, for spectral purity measurements, the analyzer must be more spectrally

pure than the signals it measures, and noise sidebands can limit resolution. Noise sidebands are specified as so many dB down from the carrier in a specific bandwidth. For example, the 8553B, .001 - 110 MHz spectrum analyzer, noise sidebands are more than 70 dB down, 50 kHz away from the carrier in a 1 kHz bandwidth.

STABILIZATION: To reduce the analyzer residual FM in narrow scans, one of its sweeping local oscillators (normally the first LO) is synchronized to a stable crystal oscillator. Two techniques are used, automatic phase control (APC, i.e., phase lock) and automatic frequency control (AFC, i.e., frequency lock). Fundamentally, these techniques are simple. In phase lock, the analyzer LO is mixed with a crystal signal (or harmonic), the output is fed to a phase discriminator and the output of the discriminator (the error signal) is summed with the LO tuning voltage. It should be noted that the output of the phase discriminator is a function of the phase difference between the two signals, this explains the name phase lock. Frequency lock is similar except that the output of the discriminator (correction signal) is a function of the frequency difference between the LO and crystal harmonic, therefore the smaller the difference the smaller the correction.

In a well designed stabilization technique, the signal remains on-screen when switching from unstabilized to stabilized operation. This is a feature of all HP stabilized analyzers.

HARMONIC MIXING: Harmonic mixing is a technique used to extend the frequency range of the spectrum analyzer. A response is displayed on the CRT when

$$F_s - F_{LO} = F_{IF} \text{ and } F_{LO} - F_s = F_{IF}$$

where F_s – frequency of an unknown signal
F_{LO} – frequency of the analyzer local oscillator
F_{IF} – first IF frequency of the analyzer
or, $F_s - F_{LO} = \pm F_{IF}$ so that $F_s = F_{LO} \pm F_{IF}$

A more general form of this formula is

$$F_s = nF_{LO} \pm F_{IF}$$

where n is the harmonic number of the analyzer local oscillator. Thus, by mixing with the harmonics of the local oscillator, we can extend the analyzer frequency range to higher and higher frequencies.

IMAGE RESPONSES: Image signals are a pair of frequencies separated by twice the IF frequency of the analyzer. When image signals are applied to the analyzer and no filtering is done in the input circuit the two image signals mix with the same LO frequency (or harmonic) and appear as one response on the CRT, hence the name "image responses." (They are mirror images around the LO frequency.) For example, with a 2 GHz IF frequency, 1 GHz and 5 GHz are image frequencies and so are 10 GHz and 14 GHz, i.e., a pair of image responses exists for the LO fundamental frequency and each of its harmonics.

In the harmonic mixing analyzer, no filtering is done at the input so image responses may occur and produce a misleading display. Thus, there must be a way to eliminate image responses. The tracking preselector (see below) is a device that eliminates image and many other unwanted products.

MULTIPLE RESPONSES: When a signal is connected to the analyzer, one expects to see a single response on the CRT. In the harmonic mixing analyzer, one signal may produce several responses by mixing with more than one local oscillator frequency/harmonic in different mixing modes. For example a 5 GHz signal produces three responses as follows:

n = +1 it mixes with the GHz LO fundamental
(5 – 3 → 2 GHz 1st IF)

n = −2 it mixes with the 2nd harmonic of 3.5 GHz
(2 x 3.5) − 5 → 2 GHz 1st IF

n = −3 it mixes with the 3rd harmonic of 2.33 GHz
(3 x 2.33) − 5 → 2 GHz 1st IF

A tracking preselector also eliminates multiple responses.

IF FEEDTHROUGH: In the harmonic mixing analyzer a signal equal in frequency to the 1st IF will lift the entire baseline regardless of the frequency control settings. This phenomenon is known as IF feedthrough. Lifting the baseline, of course, obscures the display and may completely submerge other signals present. Thus to eliminate any gap in the analyzer frequency coverage, an *alternate IF must be available* and the two IFs must not be harmonically related. A preselector also eliminates IF feedthrough.

PRESELECTOR: The preselector is a voltage tunable bandpass (typically 20-50 MHz) filter which tracks the analyzer tuning. It is used with the harmonic mixing analyzer to eliminate image, multiple and spurious responses.

The preselector generally uses an yittrium-iron-garnet (YIG) material. The YIG tuning properties extend typically from 1.8 - 18 GHz.

DISPLAY RANGE: This refers to the difference (in dB) between the top line of the CRT and the lowest utilizable (calibrated) line. This range is limited by the screen size and the log amplifier.

DYNAMIC RANGE: Is the ratio of the largest signal to the smallest signal that can be displayed *simultaneously* with no analyzer distortion products. There is an optimum signal level associated with dynamic range, reducing the signal level at the input mixer by 10 dB increases dynamic range by at least 10 dB, assuming there is sufficient sensitivity. This definition of dynamic range means distortion-free display range. All signals displayed on the CRT are real signals and not analyzer distortion or spurious mixing products. This definition is not the same as the ratio of the largest signal that can be applied without serious distortion (usually means 1 dB amplitude compression) to the smallest signal that can be detected. Likewise, it is not the ratio of the largest to the smallest signal that can be measured by the analyzer.

SENSITIVITY: Sensitivity is a measure of the analyzer's capability to detect small signals. Like most receivers, the analyzer's maximum sensitivity (minimum discernible signal) is limited by the inherent average noise. Thus, an unknown signal can be detected when the signal power = inherent average noise power, or

$$\frac{\text{Signal power + inherent average noise power}}{\text{inherent average noise power}} = 2$$

When viewed on the CRT, this signal appears 3 dB above the inherent average noise level.

Referred to the analyzer input, the inherent average noise level has two components; thermal noise and noise resulting from the active elements. Thus,

$$P_{in} = 10 \log KTB + N_a$$

where:

P_{in} = inherent average noise in dBm
K = Boltzmann's constant—joules
T = Absolute temperature − °K
B = Equivalent IF bandwidth − Hz
N_a = The analyzer noise figure − the contribution of the active elements − dB

From this definition, we can see that the inherent average noise is bandwidth dependent, e.g., −110 dBm/10 KHz. Because of the power relationship above, a decade decrease in

bandwidth results in 10 dB lower noise level and consequently 10 dB better sensitivity. When measuring inherent average noise level, a video filter with a bandwidth much less than the IF bandwidth should be inserted in the output circuit and the analyzer input should be terminated with its characteristic impedance.

OPTIMUM INPUT LEVEL: This refers to the signal level into the input mixer which ensures that the analyzer generated distortion products are below a certain level. For example, a −40 dBm optimum level into the mixer guarantees distortion products to be below −110 dBm, i.e. 70 dB down. The 70 dB range is the dynamic range defined above. Different mixers have different optimum levels, however, most HP spectrum analyzers specify −40 dBm to be the optimum input level.

LINEAR INPUT LEVEL: This is also a characteristic of the input mixer and it refers to an upper signal level for which amplitude compression is less than 1 dB. Above this level, the mixer goes into serious gain compression (1 dB compression equals a 12.2% error) and becomes non-linear, i.e., the mixer output is no longer proportional to the input signal level. Linear operation means amplitude compression is <1 dB, it does not mean the display is distortion-free. Distortion will be generated for input levels in the mixer above the optimum value.

MAXIMUM INPUT LEVEL: This is the damage level of the analyzer front-end. Two figures are usually given; one is the burn-out level of the mixer and the other is the damage level of the input attenuator. For example, −13 dBm may be the mixer burn-out level and +30 dBm the damage level for input attenuator.

AMPLITUDE ACCURACY: This refers to the error of the amplitude calibration of the analyzer. This error consists of several components; i.e., flatness, switching input attenuator, switching between bandwidths, IF gain of the log amplifier, amplitude display and the built-in calibrator. With IF substitution, this error can be reduced to the sum of the frequency response variations and the IF gain accuracy (log reference level control).

FLATNESS: Flatness is the term used to describe the frequency response variations of the spectrum analyzer. A ± 1 dB flatness means the peaks and the troughs of the frequency response of the analyzer are 2 dB apart.

AMPLITUDE DISPLAY ACCURACY: This is the accuracy of relative amplitude measurements made from the CRT scale.

LOG DISPLAY: A display mode in which the CRT vertical deflection is a logarithmic function of the input signal voltage. In this mode, the CRT is calibrated in dBm in most HP analyzers. dBμV and dBmV calibrations are also used.

LINEAR DISPLAY: A display mode in which the CRT vertical deflection is directly proportional to the RMS input signal voltage. In this mode, the CRT is calibrated in volts in most HP analyzers. In the HP economy analyzers, however, the linear mode has no scale calibration but the reference level is calibrated in dBm.

LOG REFERENCE LEVEL OR REFERENCE LEVEL: This refers to the absolute calibration of the top graticule line of the CRT. All HP analyzers are absolutely calibrated in amplitude, Log Reference Level is generally calibrated in dBm (0 dBm = 1 mW). Other calibrations such as volts, dBμV, dBmV are also used.

SPURIOUS RESPONSES: These are undesired responses that are generated in the analyzer and displayed on the CRT. There are two types of Spurious Responses; Harmonic and non-harmonic. Harmonic spurious responses are second, third, fourth, etc., harmonics of the input signal. Non-harmonic spurious responses are intermodulation and residual responses.

HARMONIC DISTORTION. When the input signal is of sufficient amplitude to drive the mixer into non-linear operation, *false* harmonics of the input signals may be generated in the mixer. These false harmonics are called harmonic distortion. Typically, second harmonic distortion is the largest component.

INTERMODULATION (IM) DISTORTION: When two strong and closely-spaced signals are fed into the analyzer input mixer, they drive the mixer into non-linear operation. This causes the two signals to interact and produce several mixing products. For example, if f_1 and f_2 are fed into the input mixer, then $2f_1 \pm f_2$, $2f_2 \pm f_1$, 2 ($f_1 \pm f_2$) and 3 ($f_1 \pm f_2$) etc. are some of the intermodulation distortion that may be seen on the CRT. $2f_1 - f_2$ and $2f_2 - f_1$ are called 3rd order IM products and are the most harmful distortion products. They are the most harmful because they are located close to f_1 and f_2; the rest of the IM products are farther removed from the spectrum of interest.

RESIDUAL RESPONSES: Responses which appear on the CRT with no input signal connected to the analyzer are called residual responses. These ever-present responses are distortion products which result when the local oscillator's fundamental or higher harmonics mix together to produce signals at one of the IF frequencies of the analyzer.

LO FEEDTHROUGH: In the scanning analyzer when the frequency of the first local oscillator is equal to the IF frequency, a response appears on the CRT. This response is known as the LO feedthrough. All HP analyzers are designed so that the LO feedthrough represents a zero frequency reference to calibrate the horizontal axis.

LO RADIATION: This is the energy detected at the front end of the analyzer. The first local oscillator feeds this energy out through the input mixer. In the absence of any input filters, the energy comes out the input connector and goes into anything connected to the analyzer.

TRACKING GENERATOR: The tracking generator is a companion instrument to the spectrum analyzer; it (the tracking generator) produces a signal whose frequency precisely tracks the spectrum analyzer tuning. In addition to the standard analyzer applications, the spectrum analyzer/tracking generator is used to make two types of measurements; frequency response of unknown devices and selective/sensitive counting of unknown signal frequencies.

TRACKING ERROR: The finite difference between the tracking generator output frequency and the analyzer tuning is called tracking error. This error affects the frequency accuracy in the tracking generator measurements and, therefore, it should be made as small as possible.

SCAN TIME: The analyzer scan time is the total time it takes to make one full sweep. It is equal to 10 x scan time/division setting.

VIDEO SCAN TRIGGER: This is a triggering mode where the analyzer sweep is synchronized to the envelope of the RF input signal. It is used to recover modulation in the zero scan mode. In HP economy analyzers, this mode is called INT.

VIDEO FILTER (or DISPLAY SMOOTHING): The video filter is a post-detection averaging device which is used to average the noise present in the analyzer. Noise averaging filters are low pass filters whose bandwidth should be much narrower than the resolution bandwidth of the analyzer. However, since the video filter is located after the IF bandwidth, it does not affect frequency resolution.

In some measurements, e.g. AM, FM and pulsed RF demodulation, the video filter bandwidth should be equal to or greater than the IF bandwidth so as to pass the demodulated waveform without distortion. Thus, measurement flexibility requires the analyzer to have wideband as well as narrowband video filters and selection of video bandwidth should be accomplished easily and quickly.

IMPEDANCE: This is the input impedance of the analyzer. 50 Ω is the most commonly used, although 75 Ω is also widely used. 1 M Ω is used in the audio frequency range.

Appendix C. List of abbreviations

AC	Alternating Current
AC1-8	AirCraft codes 1 to 8
ADC	Analog to Digital Converter
ADJ	ADJust
AFC	Automatic Frequency Control
AGC	Automatic Gain Control
ALC	Automatic Level Control
AMP	AMPlifier
ATR	Anti-Transmit-Receive
ATU	Aircraft Tracking Unit
AUTO	AUTOmatic
AUX	AUXiliary
BCD	Binary Coded Decimal
C	radar constant
c	speed of light in free space
Cal	Calibrate
CB	C-Band
CDR	Circular Depolarization Ratio
coax	coaxial
COHO	COHerent Oscillator
CRT	Cathode Ray Tube
CW	Continuous Wave
cw	clockwise
ccw	counter-clockwise
dB	deciBel
dBm	deciBel referenced to 1 milliWatt
DC	Direct Current
DET	DETector
DIFF	DIFFerential
EXT	EXTernal
GHz	GigaHertz
Hz	Hertz
IF	Intermediate Frequency
INT	INTernal INTegrator
kHz	kiloHertz
LED	Light Emitting Diode
LHC	Left-Hand Circular
LHE	Left-Hand Elliptical
LO	Local Oscillator
LOG	LOGarithimic
MDS	Minimum Detectable Signal
MFC	Manual Frequency Control
MHz	MegaHertz
RF	Radio Frequency
Rx	Receive
SB	S-Band
SCDR	S-Band CDR
Scope	Oscilloscope
STALO	STAble Local Oscillator
SZ	S-Band reflectivity video
THR	THReshold
TR	Transmit Receive
Tx	Transmit
V	Volt
WAZ	Weather radar AZimuth
WEL	Weather radar ELevation
WR	Weather Radar
Z	equivalent reflectivity

Appendix D: Glossary

Antenna Gain: A measurement of an antenna's ability to focus the RF energy to be transmitted or received in a given direction, as compared to a nondirectional antenna. Gain is specified in dB.

Attenuation: A measurement of signal loss expressed in dB.

Axial Ratio: For an elliptically polarized wave, the axial ratio is defined as the ratio of the major axis to the minor axis of the ellipse.

Beam Width: The angle between the points where the power is 3 dB down from the peak power measured in the center of the beam. This is a specification which could have different values for different axes.

Cavity: A volume enclosed by a conducting surface within which an electromagnetic field can be excited. The frequency of the electromagnetic field is called the resonant frequency of the cavity.

Decibel: A measurement of power ratios defined as: $P\,(dB) = 10 \log_{10} \frac{P \text{ measured}}{1 \text{ watt}}$

Decibel Milliwatt: A measurement of power ratios defined as: $P\,(dB) = 10 \log_{10} \frac{P \text{ measured}}{1 \text{ milliwatt}}$

Demodulation: The process of recovering information from a modulated signal.

Doppler Effect: A frequency shift caused by differential motion between a frequency transmitter and a frequency receiver.

Fourier Analysis: Fourier analysis represents all waves as the sum of sinsoidal waves of different frequencies. This concept is used to separate signals into their frequency components which can then be observed on a spectrum analyzer.

Impedence: The combined effect of resistance and reactance of a circuit element. Expressed in ohms and including a phase angle.

Insertion Loss: The loss in power between two points on a transmission line or the power loss passing through a device.

Isolation: A measure of a desirable loss or reduction in power between two channels or ports in a system.

Load: A general term for circuit elements or devices connected to a signal source.

Magnetron: A microwave tube used to generate non-coherent high power RF. A magnetron will oscillate when a high power pulse is applied. Coaxial Magnetrons have internal structures resembling coaxial lines. They are becoming common because a coaxial magnetron is more reliable than a standard magnetron.

Microprocessor: (MPU) A complex logic element which performs arithmetic, logic, and control operations and which is generally packaged as a single integrated circuit (IC).

Microcomputer: A single LSI device acting as a complete computer system. The device integrates a microprocessor, memory, and I/O interface on a single chip.

Microcomputer System: The combination of a microcomputer, a mechanical enclosure, and power distribution functioning as a complete computer system.

Match, Mismatch: When the impedance of a load is equal to the impedance of a signal source, the system is matched. When the impedances are not equal, causing signal reflections within the system, the system is mismatched.

Orientation: The angle between the minor axis of an elliptical wave and the vertical axis.

Polarization: The polarization of an electromagnetic wave refers to the direction in free space in which the electric field strength vector of the wave is varying.

Resolver: A 4-wire shaft angle information transmission system similar to synchros.

Spiral Scan: An antenna elevation program which causes antenna elevation to change as a function of cumulative azimuth position.

Step Scan: An antenna program in which the antenna is elevated in steps per azimuth revolution.

Synchro: A 3 wire shaft angle information transmission system used in antenna elevation and azimuth angle indicators.

Appendix E: Calibration and check sheets

Midnight Shift Systems Check List
X-Band Receiver Checks
C-Band Major Calibration
S-Band Antenna and Phase Discriminator Calibration
S-Band Major Calibration
Daily Operation Checks
Transponder Checks
Radar Systems Status Check List

Supervisor: _____ Date: _____

Time: _____

Midnight Shift Check List

Check if okay, X if not okay, correct and enter in radar log

S Band Major Calibration ___

S Band Antenna, Phase Discrimination Calibration ___

C Band Calibration ___

X Band Receiver Checks ___

Transponder Maintenance ___

Tape Drive Cleaned ___

Bit Check AZ ___ EL ___ AC AZ ___ AC RG ___

Plan Position Indicators

Parameter	Control Consol	Storm Chase	Radar
Grey Shades			
Range Rings			
A/C with A/C Simulator			

X-Band receiver checks

Receive frequency check
Attenuation _____
STC Switch to Off

Name _____
Date _____
Time _____
Supervisor _____

Set Pulse - 400 μs delay, 10 μs wide

Present frequency: (MHz)_____
LO Setting:_____
Tuned to: (MHz)_____
New LO Setting_____

Receiver sensitivity

0.5 μs MDS: (-dBm)_____
10 μs MDS: (-dBm)_____
Noise Average: (volts)_____
Noise Peak: (volts)_____

TTL noise threshold check

Set Pulse - 400 μs delay, 0.5 μs wide

Threshold Setting:

TTL MDS OFF: (-dBm)_____
TTL MDS ON: (-dBm)_____

Set STC switch to On

Remarks:

C-Band major calibration

Logarithmic amplifier and integrator calibration

Name _____

Date _____

Time _____

Supervisor _____

Setup 1. Frequency control to MANUAL
2. Log Amp Pulse - 45 μs delay, 10 μs wide
Integrator Pulse - 450 μs delay, 100 μs wide

Temperature _____, Frequency _____, Attenuation _____

Log Amp: MDS = _____ -dBm Noise = _____ volts

Integrator MDS = _____ -dBm Noise = _____ volts

Power Injected (-dBm)	Log Amp (volts)	Integrator (volts)
95		
90		
85		
80		
75		
70		
65		
60		
55		
50		
45		
40		
35		
30		
25		
20		
15		

Threshold check

Setup 1. Pulse - 450 μs delay, 100 μs wide

Level (-dBm)	Threshold (-dBm)	Grey Scale (volts)
1 (94 to 79)		
2 (79 to 64)		
3 (64 to 54)		
4 (54 to 44)		
5 (44 and up)		

File Names: Port 6 _____, _____, _____

Return frequency control to automatic

S-Band antenna and phase discriminator calibration

Isolation check (part 1)

Name _____

Date _____

Time _____

Supervisor _____

Setup 1. Antenna Poliarization - LHC
Setup 2. Monitor - ON
Setup 3. Monitor Polarization - LHC
Setup 4. IF Switch - Test Receiver

Attenna Position
Azimuth _____
Elevation _____

Port 1 meter reading _____ with _____ dB inserted
Port 2 meter reading same as above with _____ dB inserted

Isolation _____ dB (Port 1 dB inserted - Port 2 dB inserted)

Signal to noise ratio check

Setup 1. Antenna Polarization - LHC
2. Monitor Polarization - LINEAR
3. Monitor - OFF

Port 1 meter reading _____ with _____ dB inserted
Port 2 meter reading _____ with _____ dB inserted

Monitor ON, adjust Test Receiver to noise readings.

Port 1 = _____ dB inserted — S/N Ratio = _____ dB
Port 2 = _____ dB inserted — S/N Ratio = _____ dB

Phase discriminator calibration

Setup 1. IF Switch to LOG AMP -ϕ DISC

Phase Shifter Setting (degrees)	Phase INT 3 (volts)	Phase INT 4 (volts)	Phase Shifter setting (degrees)	Phase INT 3 (volts)	Phase INT4 (volts)
360			180		
340			160		
320			140		
300			120		
280			100		
260			80		
240			60		
220			40		
200			20		
180			0		

Computer phase calibration

File Names: Port 3 _____, _____, _____

Port 4 _____, _____, _____

Isolation check (part 2)

Setup 1. Antenna Polarization- LHC
Setup 2. Monitor - ON
Setup 3. Monitor Polarization - RHC
Setup 4. IF Switch - Test Receiver

Port 2 meter reading _____ with _____ dB inserted

Port 1 meter reading same as above with _____ db inserted

Isolation _____ dB (Port 2 dB inserted - Port 1 dB inserted)

Return monitor to LHC
monitor to OFF
If switch to LOG AMP - (ϕ) Disc

Remarks

Name _____

Date _____

Time _____

Supervisor _____

S-Band major calibration

Logarithmic amplifier and range integrator calibration

Setup 1. Antenna: LINEAR

Room Temp _____; Attenuation _____ dB old/new Frequency _____

Log Amp: MDS Port 1 = _____ -dBm Port 2 = _____ -dBm

Noise Port 1 = _____ volts Port 2 = _____ volts

Range Integrator: MDS Port 1 = _____ -dBm Port 2 = _____ -dBm

Noise Port 1 = _____ volts Port 2 = _____ volts

Setup 1. Logarithmic Amp Pulse - 45 μs delay, 10 μs wide

Range Integrator Pulse - 450 μs delay, 100 μs wide

Power Injected (-dBm)	Port 1		Port 2	
	Log Amp (volts)	Integrator (volts)	Log Amp (volts)	Integrator (volts)
100				
95				
90				
85				
80				
75				
70				
65				
60				
55				
50				
45				
40				
35				
30				
25				
20				
15				

Threshold (Port 2) Check Setup 1. Pulse - 450 μs delay, 100 μs wide

Level (-dBm)	Threshold (-dBm)	Grey Scale (volts)
1 (100 to 82.5)		
2 (82.5 to 70.0)		
3 (70.0 to 60.0)		
4 (60.0 to 50.0)		
5 (50.0 and up)		

Differential amplifier calibration

Setup 1. Antenna - LINEAR
2. Pulse - 450 μs delay, 100 μs wide @ - 40 dBm

Attenuation required in Port 1 to obtain -5 dBm CDR = _____ dB

Input to Pre-amp 1 by IF attenuation (-dBm)	Integrator 1 output from previous sheet (volts)	CDR (-dBm)	Attenuation inserted Port 1 (dB)	Diff Amp output (volts)
40			0	
45			5	
50			10	
55			15	
60			20	
65			25	
70			30	
75			35	
80			40	
85			45	
90			50	
95			55	

CDR Threshold Setup 1. Pulse - 450 μs delay, 100 μs wide

Level (-dBm)	dB inserted Line 1	Grey Scale Output
1 (5 to 10)		
2 (10 to 15)		
3 (15 to 20)		
4 (20 to 25)		
5 (25 and Down)		

Differential amplifier gate

Attenuation in Port 1 to turn Differential Amplifier output off = _____ dB

Return attenuators to 0 db

Computer calibration

File Names: Port 1 _____, _____, _____
Port 2 _____, _____, _____

Remarks:

Daily Operational Check List. Check/if okay, X if not okay, correct and enter in the radar log.

Radar Checks

Time of Check										
Radar S, C or X										
Frequency Tx (GHz)										
Power: peak (dBm)										
(kw)										
average (dBm)										
(kw)										
Return loss (dB)										
3 dB BW (MHz)										
Pulse Width (us)										
Elevation Sequence										

Transponder checks

Name							
Date							
Time							
Supervisor							
Serial Number:							
Code:							
Power supply:							
Voltage: (volts)							
Current (Quiescent): (mA)							
Receiver							
MDS at 9475 MHz: (-dBm)							
Receive Frequency: (MHz)							
Transmitter							
Transmit Frequency: (MHz)							
Pulse Separation: (μs)							
Output Power Average: (-dBm)							
Output Power Peak: (-dBm)							
Power Supply							
Current (Interrogated): (mA)							

Remarks

Radar Systems Status

Date: _____

Signature: _____

___ Fully Operational

N Conditionally Operational
↑ Condition index #

N Equipment Failure
↑ Estimated repair time

Radar

	C Band	S Band	X Band
Transmitter			
Receiver			
Antenna			
Antenna Motion			
Computer Interface			

Display and Remoting

	Seeding Control	Storm Chase	Radar Trailer
Video			
Azimuth			
Numeric Display			
Communications Link			

Computer

	11/34	11/44
CPU/Disk		
Tape Drive		
Terminals		
Software		

Auxiliary

Heating/Cooling		Generator	

Condition listing on margin or back of this page

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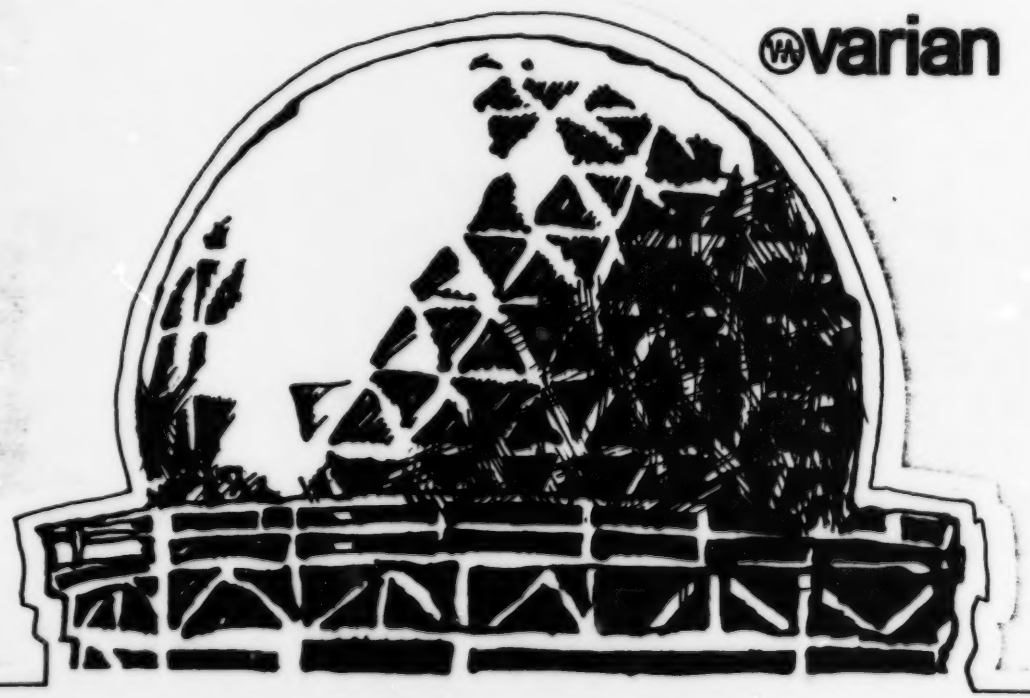

HOW TO SPEAK RADAR

BASIC FUNDAMENTALS AND APPLICATIONS OF RADAR

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FOREWORD

The following information is presented to give the reader a basic introduction to the subject of radar and to the application of radar equipment.

Historically, the original radar equipments were produced to detect and locate enemy ships and airplanes during the early days of World War II. The invention of radar is generally recognized as an invention of the British who operated the early radar systems at the now unseemly frequencies of 25 MHz. The evolution of the art has grown steadily to the present level that employs sophisticated, computerized techniques and it has stimulated the development of increasingly complex components that have been needed to continually advance the art of gathering and applying information to achieve some objective. The different kinds of radar equipment are manufactured to perform a variety of functions, but they have one common purpose: the extraction of information from a reflected radio signal. A radar equipment is simply an information machine. The kind of information and the resolution or accuracy of that information is a measure of the radar and can vary appreciably according to the objective the radar is to accomplish.

The word RADAR is an acronym coined from the expression RAdio Detection And Ranging. As the following discussion will indicate, the original objectives of detection and ranging have grown to include desired radar imagery that tries to approach that of light photography.

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HOW TO SPEAK RADAR

GENERAL

Uses of Radar

An equipment that uses the principles of radar is called a radar system. Such a system can be small enough to install in an automobile spotlight, such as a police speed-detection radar, or large enough to require one or more buildings to enclose a single radar system.

Some functions of radar systems are listed below together with an example of a typical radar system for each function.

Function	Example
1. Search	Early Warning Radar
2. Locate	Mortar Locater
3. Control	Air Traffic Control Radar
4. Navigate	Terrain Following Radar
5. Track	Satellite Tracking Radar
6. Map	Side-Looking Radar
7. Intercept	Attack Radar
8. Guide	Missile Illuminator
9. Identify	Missile Defense Radar
10. Measure	Velocimeter Radar
11. Warn	Threat Warning Radar
12. Dock	Capsule Docking Radar

Desired Information

In performing the above functions, the radar systems must obtain certain information from the radar signal. The kinds of radar information that can be extracted include:

1. Range
2. Range rate or velocity
3. Azimuth (angular) direction
4. Elevation angle
5. Target size
6. Target shape
7. Change in target shape
8. Particular target identification or "target signature"

Measurement Information

The extraction of information from the returned "echoes" of a radar transmitter is performed by analyzing the returned signals in terms of (1) the time of arrival of signals and (2) the detected frequency changes or phase changes of the signal. In the first instance, measurements are made in the time domain. By knowing that the velocity of propagation of a radiated signal is equal to the velocity of light and by measuring the time elapsed between transmission and reception, the distance that the signal traveled can be determined and displayed. Thus, range measurement is made in the time domain. (Distance = Time x Velocity.)

When a signal is reflected from a target moving in a relative radial direction, an effective shift in frequency is experienced. This frequency shift is known to be caused by the Doppler Effect (page 3), and the magnitude of the frequency shift is measured by determining the frequency difference between the transmitted frequency and the frequency of the returned signal. This measurement is made in the frequency domain and is the means of determining the relative radial velocity of a moving target in relation to the position of the radar. In a sophisticated radar, measurements may be made in both time and frequency domains in order to extract as much available information from the returned signal as can be obtained within the present art.

Resolution Information

The degree of resolution of radar information is defined as how well a radar system can separate two signals that are either close to each other in terms of time measurement (range) or frequency measurement (velocity). Obtainable resolution depends upon: (1) the amount of information transmitted (bandwidth and modulation); (2) the manner in which the transmitted signal is directed and received (antenna directiveness); and (3) the manner in which the returned signal is detected and processed.

Range resolution is obtained by using either (1) very short transmitted pulses so that targets that are close together can be detected at different times, or by (2) employing modulation to the pulse to enable discrimination between two signals that are received simultaneously. This is described later in the section on Pulse Compression, (page 10).

Angular (azimuth) resolution depends upon the beam width of the antenna. Angular resolution decreases as the range increases, since the antenna beam becomes wider with increased range. The obvious way to increase angular resolution is to employ a very directional antenna beam that is as narrow as can be achieved. A second method is to apply sophisticated doppler sensing techniques as is described later in the discussion on Synthetic Aperture Radar Systems, (page 16).

Velocity resolution depends upon the ability of the receiver and the detector to discriminate in frequency. Velocity measurements are achieved with a group of doppler filters and the discrimination between adjacent doppler frequencies is then determined by the frequency bandwidth and selectivity of each doppler filter.

Generally, the factors that increase resolution can be summarized as follows:

Ambiguous and Unambiguous Information

The word "ambiguous" is used frequently in radar system design considerations when speaking of extracting information when either (1) more than one choice is available for the correct information, making the correct value uncertain, or (2) there are conditions that do not allow the correct information to be extracted. If a measurement can be made in a continuous manner, the measurement is an unambiguous one. For example, if velocity is measured by measuring the doppler frequency shift of a CW transmission, the measurement is a continuous one and all velocity information is available to measure. However, if the CW transmission is interrupted at some periodic rate, the velocity information that corresponds to the frequency of interruption and its multiples cannot be measured. This condition defines ambiguous doppler effect measurements, and the relationship to pulse recurrence frequency is shown in Figure 1.

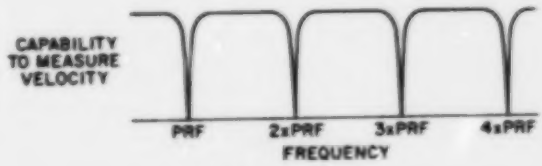


Figure 1

Velocity frequency measurement capability as a function of frequency of interruption (PRF).

In the case of range measurement, if only one pulse is transmitted, all ranges can be measured with no ambiguity. However, as soon as a second pulse is transmitted, unambiguous range measurements have a definite limit before becoming ambiguous.

If a reflected signal appears at the same time as the next pulse is transmitted, the signal is not

TIME DOMAIN		FREQUENCY DOMAIN
Angular Resolution	Range Resolution	Velocity Resolution
1. Narrow Antenna Bandwidth High Operating Frequency Large Antenna Aperture 2. Doppler Sensing	1. Short Pulse Width 2. Pulse Compression	1. Narrow Doppler Frequency Filter Bandwidth

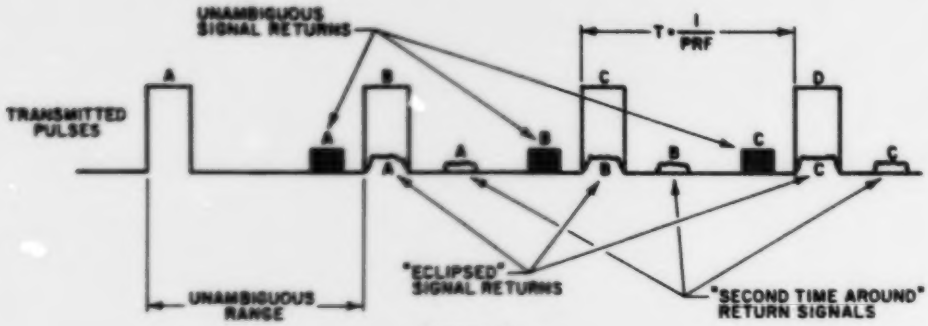


Figure 2

Signal returns in range measurements.

able to be detected and is said to be "eclipsed". If a reflected signal appears after the next pulse is transmitted, the signal is received as an ambiguous signal and is referred to as a "second time around" target. Figure 2 diagrams the time relationship of various return signals in range measurements.

The Doppler Effect

Doppler Effect is that effect which gives an apparent change in frequency if either the source of radiating energy or the reflecting target is in motion relative to the other. Doppler frequency shift is a function of the relative velocity and the oscillating frequency and their relationship is shown in the formula:

$$F_d = \frac{2V_r}{\lambda} = \frac{2V_r F_o}{c}$$

where:

F_d = Doppler Frequency Shift

V_r = Relative Velocity

λ = Wavelength

F_o = Transmitted Frequency

c = Velocity of Propagation

From the above equation, we learn that a radial velocity of one nautical mph provides a doppler frequency shift of about 34 Hz at an oscillating frequency of 10 GHz.

Note that the relative velocity parameter is important in measuring doppler frequency shift, since a vehicle moving at a high velocity in a circle about a fixed radiating source does not create a doppler frequency shift, as the distance between the two objects does not change. Further, if the vehicle and the radar are moving in a straight line at the same velocity and in the same direction there is also a zero doppler effect between the two.

Types of Radars by Waveform

Obviously, to obtain various kinds of information, different techniques must be used to optimize the kind of information desired. Thus, radar systems fall into the following categories according to the "waveform" or mode of operation that is employed in a radar system.

1. CW (continuous wave)
2. FM-CW (frequency modulated, continuous wave)
3. Pulse
4. Pulse Doppler
5. Monopulse

Radar Techniques

Radar system manufacturers, in their attempt to make their products as saleable as possible, try to incorporate as many state-of-the-art techniques as are economically feasible. Some of the more popular techniques now being used include:

1. Short Pulse Transmission
2. Digital Data Processing
3. Pulse Compression
4. Pulse Coding (form of pulse compression)
5. Phase Coherency (pulse-to-pulse phase relationship)

6. Coherency-on-Receive (inter-pulse phase relationship)
7. MTI (moving target indication)
8. Frequency Agility
9. Polarization Agility
10. Electronic Scanning (phased arrays)
11. Synthetic Aperture Antennas

The above items become some of the selling features of radar system manufacturers in their selling efforts to their customers. Again, the amount and quality of information that a radar system can extract from an operating environment is a measure of that system. Other factors include system acquisition cost, maintenance costs, efficiency of operation, and reliability.

The Radar Equation

A radar system uses the phenomenon of a body reflecting (repropagating) high-frequency electromagnetic energy, to obtain an "echo" return to a high frequency transmission. The manner in which a wave of energy is transmitted (the waveform) and received is a choice that is always fitted to the intended use of a radar equipment. Generally, one particular measurement is desired most, such as range, so that other information (velocity, elevation, etc.) may be compromised, if necessary, as a less important objective.

The detection performance of any radar depends upon many factors that are related in what is traditionally known as the Radar Equation. There are a number of forms of this equation. One common form equates the ratio of the returned signal power, S, to the receiver noise power, N, as shown in the following:

$$\frac{S}{N} = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4 \overline{NF} kTB L}$$

where:

P = Transmitted Power

G = Antenna Gain

λ = Wavelength

σ = Target Cross Section

R = Range of Target

$\overline{NF}$ = Noise Figure of Receiver

k = Boltzman's Constant

T = Temperature

B = Bandwidth

L = Assorted Losses

The radar equation is derived in the following steps:

1. The power density at a target at range R is equal to the peak power radiated from a transmitter divided by the area of a sphere of radius R.

$$P_d = \frac{P}{4\pi R^2}$$

2. If the signal is directed by an antenna with gain, G, then

$$P_d = \frac{PG}{4\pi R^2}$$

3. The reflected power density from the target will be a function of the target cross section, σ. The reflected power from the target is

$$P_r = \frac{PG\sigma}{4\pi R^2}$$

4. The power density of the reflected signal at the radar is

$$P_d = \frac{PG\sigma}{(4\pi R^2)^2}$$

5. The power of the reflected signal, S, at the radar is the product of the power density times the area of the antenna. (A = aperture)

$$S = \frac{PG\sigma A}{(4\pi R^2)^2}$$

6. Substituting the relationship of gain and aperture

$$A = \frac{G\lambda^2}{4\pi}, \text{ then } S = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

7. When equating as S/N, the noise figure of the receiver, $\overline{NF}$, and the thermal noise power, kTB, become part of the denominator.

$$\frac{S}{N} = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4 \overline{NF} kTB}$$

8. The term L, representing a number of losses in the radar system and propagation losses, is introduced accordingly, making the equation

$$\frac{S}{N} = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4 NF kTB L}$$

In a pulsed radar that operates with low pulse recurrence frequencies, typically less than 3 kHz, most of the returned energy will be utilized in detecting the received signal. The frequency spectrum as shown in Figure 10 is about $\frac{2}{\tau}$ wide, so a receiver with a few megahertz bandwidth will accept most of the energy in the returned signal. For this reason, when using the radar equation for low PRF pulsed radars, the peak value of transmitted output power is used.

In pulsed radars that operate at high pulse recurrence frequencies from 10 kHz to 350 kHz (pulse doppler types), the usable returned energy is that of one spectral line, since the principal measurement of interest is a frequency domain measurement and the frequency (doppler) information is common to each spectral line. Hence, only a portion of the returned energy is utilized and the power term in the radar equation becomes the peak transmitted power times the square of the duty cycle.

If R_o is designated as the range that provides unity S/N, then the equation becomes:

$$R_o^4 = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 NF kTB L}$$

When this range is known, then the S/N at other ranges can be calculated by using the relationship:

$$\frac{S}{N} = \left(\frac{R_o}{R}\right)^4$$

Significantly, the S/N is inversely proportional to the fourth power of range.

Knowing the above relationships, one can calculate the parameters for specified ranges that provide useful return signals.

Threshold Level and False Alarms

A radar receiver has a means of setting the "threshold level", a level a signal must exceed to be seen on an indicator or be used in some other manner. Unfortunately, noise signals are not at one constant level and can vary as illustrated in Figure 3. If a threshold level is set high enough to prevent any noise signals from appearing, the radar's sensitivity is reduced considerably. If the threshold is set too low, then too many false indications are seen and the noise signals tend to complicate detection of the desired information. Therefore, a compromise level is selected by adjusting manually or automatically for specific operating conditions. The threshold level can then set the "false-alarm rate" of the radar, which is simply the number of false-alarm signals that appear in a given time period, such as one minute. The probability of a false-alarm signal occurring depends upon the threshold setting.

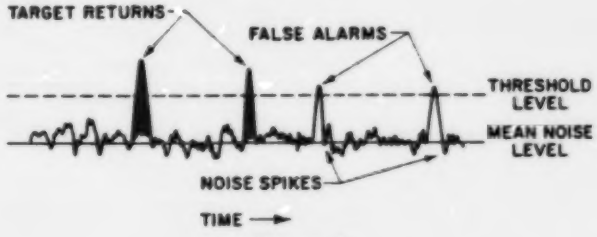


Figure 3
Comparative signal amplitudes and threshold level.

The probability of target detection depends on the relationship between signal-to-noise ratio, S/N, and the threshold setting in the detection circuitry. In the case of a moving antenna, it also is dependent upon such factors as antenna scan rate, antenna beam width, and the pulse recurrence frequency, all of which determine the "look time".

Obviously the probability of target detection is increased with a more powerful signal, more directivity, and longer transmission time at the target, together with a more sensitive receiver with a long "listen" time. Unfortunately, all of these dependent factors cannot always be applied simultaneously and performance compromises are often tolerated.

RADAR SYSTEMS

CW Systems

A CW radar utilizes the doppler effect for measurement and is used primarily where unambiguous velocity information is desired. CW

radars are usually single target devices and are used principally for (1) CW missile guidance systems (called CW illuminators, since they illuminate the target with energy), (2) velocity measuring radars, including police radars and railroad car velocity radars, (3) personnel detection radars, and (4) rate-of-climb meters.

CW Illuminators

This kind of radar transmitter is characterized by its low noise requirements. In a CW guidance mode of operation, a missile is guided by information derived from the doppler frequency shift, due to the relative velocities of the target and the missile. Since doppler frequency shifts are usually less than 100 kHz, it is extremely important to transmit a "clean" doppler signal spectrum, since a spurious doppler signal may look like a false target and can be confused with the true target doppler signal. A coded modulation capability is generally included in an illuminator to transmit information to the missile from the ground. Typical block diagrams are shown in Figure 4.

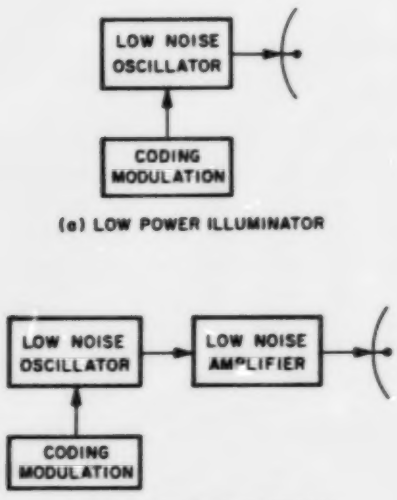


Figure 4

Illuminator radar systems block diagrams.

Velocity Measuring Devices

A typical block diagram of a velocity measuring radar is shown in Figure 5. In the case of a police radar, the transmitting tube doubles as a local oscillator to provide a difference frequency that is dependent upon the velocity of the automobile. The difference frequency is simply measured and used to provide an indication on a meter.

Personnel detection CW radars perform much like police radars except that headphones can be used to detect the doppler frequencies instead of a meter.

Rate of climb radars operate similarly, except that they detect the phase relationship of a receding or approaching target by employing two receiver channels and local oscillator signals in quadrature. Output power is generally less than one watt for police, personnel, and rate-of-climb types of radars.

CW radars are smaller than corresponding pulse radars, although two antennas are required, and can operate against targets to almost zero range. CW systems are power limited, since coupling between antennas and transmitter noise will affect receiver sensitivity.

FM-CW Systems

A CW radar to measure both range and velocity of a single target is accomplished by broadening the transmitted frequency spectrum by frequency modulating the carrier frequency. Range, in terms of time, can be determined by measuring the difference between the received and transmitted frequencies as shown in Figure 6.

When only range information is desired and the target is stationary, such as in an altimeter application, the modulation need not be linear, as shown in Figure 6, but can be sinusoidal or near sinusoidal, since only an average dif-

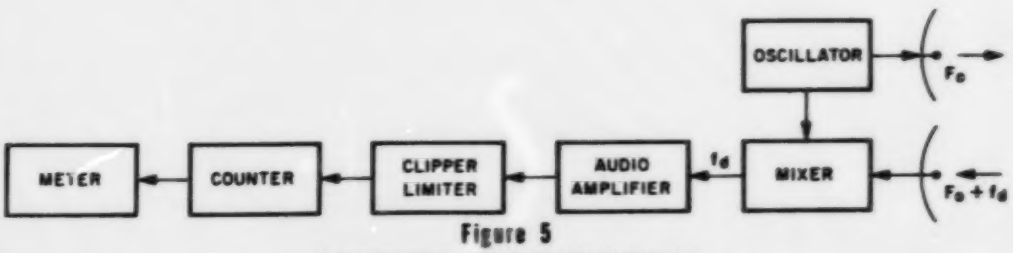


Figure 5

Velocity measuring radar block diagram.

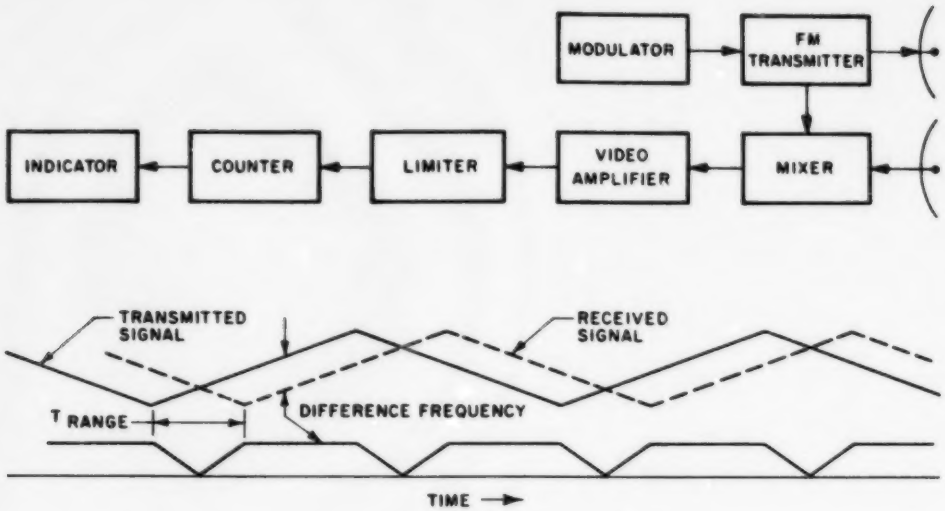


Figure 6

FM-CW range measuring radar block diagram.

ference frequency measurement is required to yield an acceptable value of range. If the target is moving, the returned signal will include a doppler shift in frequency. This information can be used to advantage in a Doppler Navigation Radar where both altitude (range) and velocity (doppler shift) information are desired. However, when doppler frequency shift information is desired, linear modulation is needed to provide an accurate measurement of doppler frequency shift. Figure 7 illustrates the frequency differences in an example where the returned signal frequency is affected by a positive doppler frequency.

The positive doppler frequency shift will have an effect on the received difference frequency, and a lesser total frequency shift will be observed if the frequency modulation is in an increasing frequency direction. When the modulation is in a decreasing frequency direction, the positive doppler effect will increase the total frequency shift. If a means is provided to measure each difference frequency, $F_o + f_d$ and $F_o - f_d$, then the difference between the two frequencies is twice the doppler shift and can be used accordingly to measure velocity. Figure 8 is a simplified block diagram of an FM-CW radar that can extract the average frequency difference (range) as well as the doppler frequency shift (velocity).

Another method of obtaining range information in a CW radar is by expanding the transmitted spectrum to more than one transmitted frequency. If two signals are transmitted, the phase relationship between the two signals will vary as a function of range, and radars can be designed to measure range by providing an accurate phase-measuring capability. The two-frequency type of radar is adaptable to surveying applications.

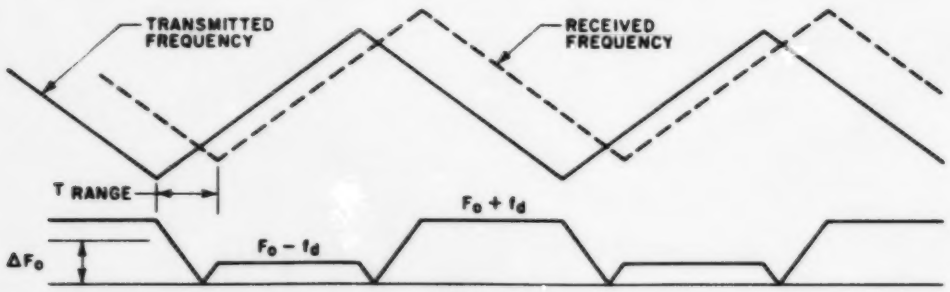


Figure 7

Doppler effect on the difference frequency in an FM-CW radar.

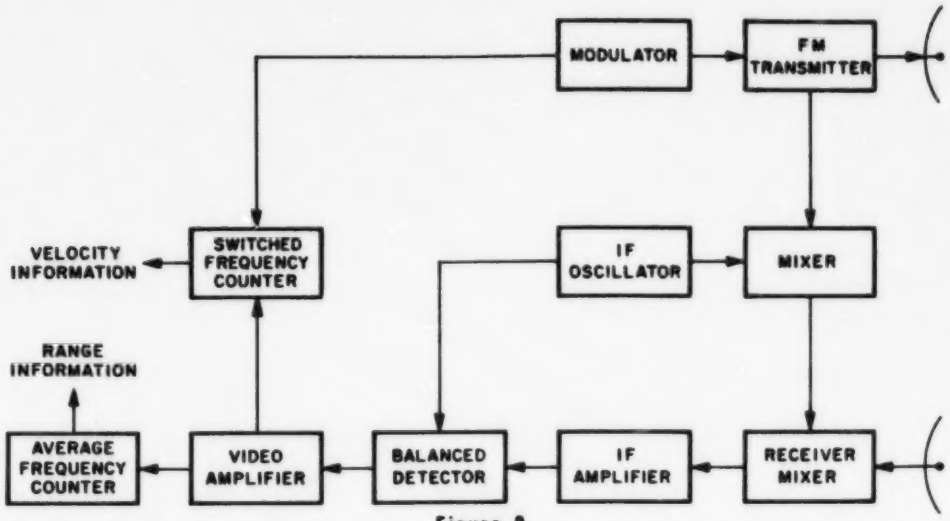


Figure 8

Range and velocity measuring FM-CW radar

Pulse Systems

Elements of Pulse Modulation

A pulse radar can be considered an expansion of a CW radar with increased transmitted-spectrum bandwidth accomplished by pulse modulation. Pulse modulation is generally applied, as shown in Figure 9, at a periodic rate known as the Pulse Recurrence Frequency (PRF). The transmitted spectrum (Figure 10), shows the energy distribution in the sidebands of the PRF, the modulation frequency, and the relationship of the pulse width, τ, to the width of the transmitted spectrum.

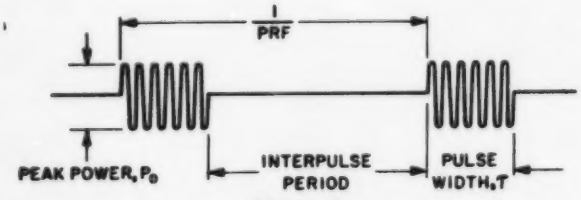


Figure 9

Pulse modulation terms.

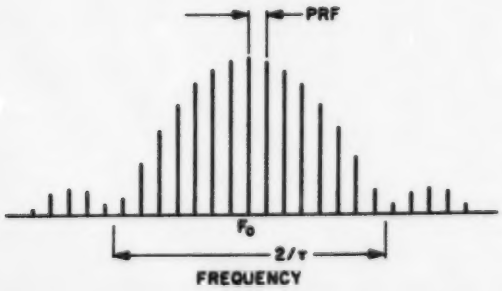


Figure 10

Pulse radar frequency spectrum.

Output power of a pulse radar is related to both pulse width and PRF. Peak output power, P_o in Figure 9, is related to the average output power by the formulas:

Pulse Width x PRF = Duty Cycle

Peak Output Power x Duty Cycle = Average Output Power

Example:

Assume a radar has a peak output of 1 megawatt, a pulse width of 1 microsecond, and a PRF of 1000 hertz. By substituting these values into the above formulas, we can determine the average output power as follows:

$$PW(sec) \times PRF(Hz) = (1 \times 10^{-6}) \times (1 \times 10^{3}) = 1 \times 10^{-3} \text{ Duty Cycle(Du)}$$

$$Po(W) \times Du = (1 \times 10^{6}) \times (1 \times 10^{-3}) = 1 \times 10^{3} \text{ W (average)}$$

The basic advantage of a pulse radar is that it provides a time interval during which the measurement of range can be accomplished by measuring the time it takes for a signal to propagate to the target and return. As mentioned previously, if a continuous transmission is interrupted, ambiguous information results. In this case, if only one pulse were transmitted,

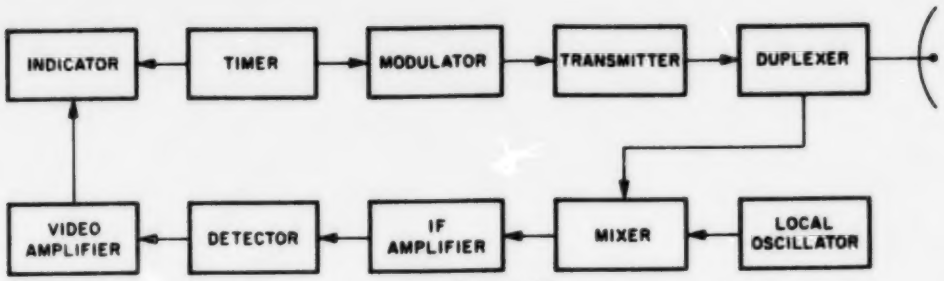


Figure 11
Pulse radar system block diagram.

any measured range (in terms of time) would be unambiguous. However, as soon as a second pulse is transmitted, unambiguous range is limited to the time period of the interpulse period. For example, a radar with PRF of 1000 hertz has a period of 1000 microseconds. Knowing that a radar signal propagates at a one nautical mile per 12.34 microsecond rate (round trip), 81 miles (1000/12.34) can be measured before the next pulse is transmitted. This is the maximum unambiguous range of the radar. Figure 11 shows a block diagram of a typical pulse radar system.

Transmit-Receive Switching

A pulse radar system can use one antenna, instead of two as required in CW systems, by using a duplexer, a device incorporating switches (gas tubes) to connect the transmitter to the antenna during the transmitted pulse, and then connecting the receiver to the antenna during the interpulse period. Gas tubes are called TR and ATR tubes and accomplish the switching action by the ionization and de-ionization of gases. The ionization and "recovery" time of these tubes play an important part in the achievable minimum range and receiver sensitivity characteristics of a radar system. Solid-state and ferrite devices are now being used frequently in radar systems to supplement or replace gas TR and ATR tubes.

Minimum Range Considerations

Some radar systems desire to "see" targets at very close ranges. When range measurement is made by using a pulsed waveform and by measuring the elapsed time between the transmitted pulse and the received signal, there are limitations to the minimum range that can be measured. The pulse width is one limitation, since the receiver cannot receive a signal until the transmitter pulse is turned off. Another limitation is the time interval required to turn the receiver on after the transmitter pulse is turned off. The latter is referred to as the recovery time and is dependent upon the switching performance of the TR and ATR tubes (or whatever devices are used) in the duplexer.

The minimum range as a function of pulse width is simply $c\tau/2$ (c = velocity of light, τ = pulse width), as the signal propagates from the time of the leading edge of the transmitted pulse. Hence, a one-microsecond pulse limits the minimum range to 492 feet (984 ft/μs x 1/2). In other words, during a one-microsecond pulse, the pulse energy from the leading edge of the pulse has time to travel 492 feet and return while the transmitter is still on. If another microsecond is needed for switching, the minimum range increases to 984 feet.

A radar system that must have short range capability must use a very short pulse width and have optimum receiver recovery time. To achieve shortest recovery time, a separate and isolated receiver antenna may be employed to eliminate the recovery time of switching devices. A radar system operating with separate transmit and receive antennas and 0.1 microsecond pulse width can realize a minimum range of 49 feet. When range measurements are made with an FM-CW radar, in which the measurements are made in the frequency domain, range can be measured to almost zero range. However, an FM-CW radar is a one target type radar, as in a radar altimeter, and is not adaptable to multi-target applications.

Receiver Bandwidth

A radar receiver must be designed to extract the maximum information out of the return sig-

nal. The bandwidth of the receiver is related to the bandwidth of the transmitted signal, usually by a factor approximating the reciprocal of the pulse width. (A radar with a one-microsecond pulse width must have a receiver bandwidth of at least one MHz in order to best utilize the energy in the pulse signal.) Pulse width is a good indication of the use of a radar, since it provides some indication of the range resolution that is desired. For example, a short pulse width (100 nanoseconds) is used for increased resolution, requiring wider bandwidth receiver components.

Operating Frequency

The operating frequency of a radar is chosen to best achieve given objectives. Angular resolution can be improved by transmitting at high frequencies, since antenna beam width can be made smaller. Higher operating frequencies allow smaller antennas, more compact equipment packaging, etc., but compromise power handling capabiltiy and experience higher propagation attenuation losses. In some applications, only short ranges are required, such as in an airport surveillance radar, and higher operating frequencies are ideal for achieving increased angular resolution. Another relatively short range radar application is in ground mapping, where increased angular resolution is very desirable. A radar frequency may be intentionally chosen at a frequency high in propagating attenuation for secure, short range operational reasons. Extremely long range radars will use lower operating frequencies to take advantage of the various propagation phenomena such as refraction effects and lower propagation attenuation. Figure 12 plots propagation attenuation loss due to water vapor as a function of operating frequency.

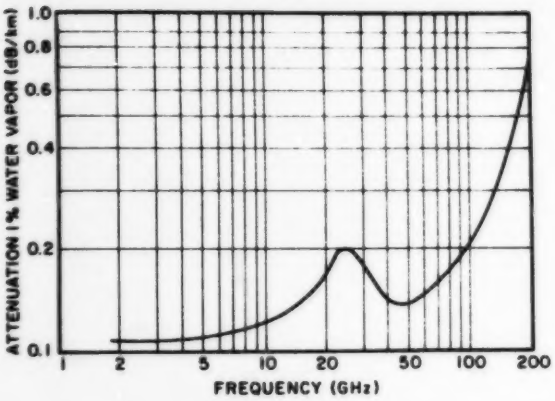


Figure 12

Generalized function of atmospheric attenuation due to water vapor.

Pulse Compression

The average transmitted power of a given radar may be increased by increasing the length of the transmitted pulse. However, this method decreases the range resolution capability of the radar by decreasing the bandwidth of the received signal. In order to provide increased pulse width without compromising range resolution, a technique is used that provides for the transmission of a long pulse that can be compressed into a short pulse length in the receiver. This technique is called Pulse Compression and is accomplished by frequency or phase modulating the transmitted pulse and then compressing the return pulse by using a time delay network whose velocity of propagation is a function of frequency. In this way, the higher frequencies "catch up" with the lower frequencies and thereby effectively shorten the pulse. A block diagram of a typical pulse compression radar is shown in Figure 13. The waveforms involved in the pulse compression technique are shown

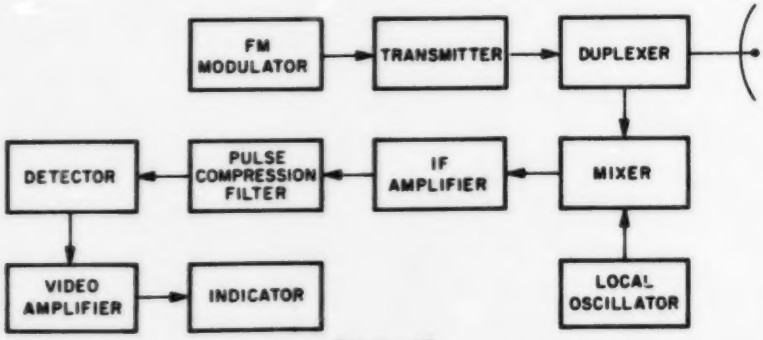
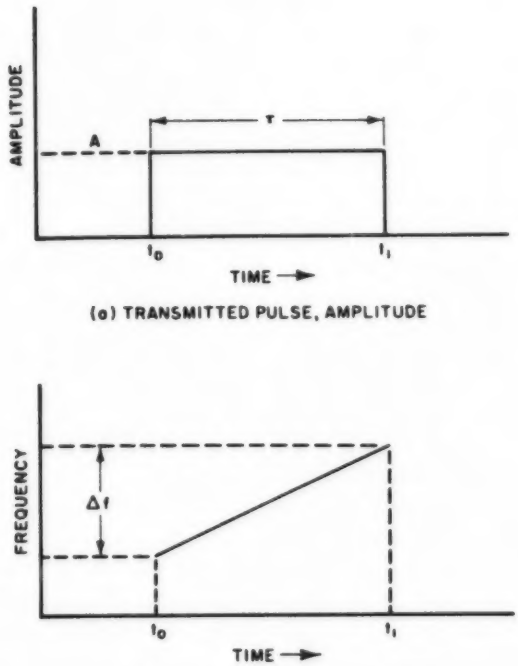


Figure 13

Pulse compression radar block diagram.

in Figure 14. The effective pulse length is compressed to a pulse length of $1/\Delta F$ and the instantaneous peak power is increased by a factor of $\sqrt{\Delta F \times \tau}$.



(a) TRANSMITTED PULSE, AMPLITUDE

(b) TRANSMITTED PULSE, FREQUENCY

(c) OUTPUT OF PULSE COMPRESSION FILTER

Figure 14
Pulse compression radar parameters.

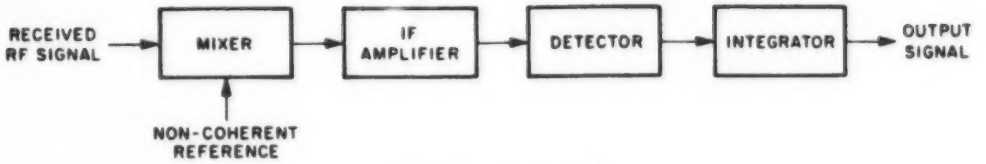
The term "pulse compression ratio" is the factor $\Delta F \times \tau$ and is typically about 100; industry is trying to achieve pulse compression ratios in the thousands. Pulse compression can also be achieved by transmitting a series of pulses that are phase coded and compressed on reception in a tapped delay line. Pulse coding can also be used in other techniques for frequency agility and for anti-ECM reasons.

Frequency Agility

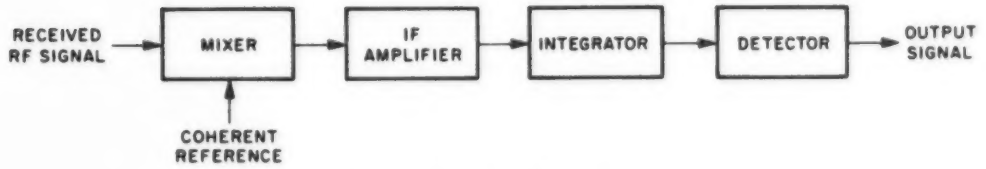
A target can be considered to be a number of point scatterers wherein the amplitude of the wave of energy reflected from the target is dependent upon the phase relationships of the reflections from the many point scatterers. If enough independent "looks" can be taken of the target, i.e., independent radiations at different frequencies to provide different reflective phase combinations, then the summation of these independent "looks" will probably result in a better target return than if the same number of "looks" were taken at one frequency and added in the same manner. This is the basis for designing frequency agile systems for purposes of increasing the detection capabilities of a radar system. Systems are also made frequency agile for reasons of anti-jam capability and for that reason the wider the operating frequency band, the better the anti-jam capability can be.

To improve the detection capability, the frequency need only be changed a small amount, sometimes referred to as "dithering". If a target size is large compared to the resolution cell of the radar, the frequency dither required to achieve the detection improvement is approximately equal to the reciprocal of the pulse width. Thus a system with a 0.5 microsecond pulse width would require only a 2 MHz frequency dither for improved performance. If the target size is smaller than the resolution cell of the radar, the required frequency dither is a number approximating 150/D, where D is the target size. Thus, a 5 meter target would require 30 MHz of frequency dithering. The change of frequency need not be periodic or random but at least 20 pulses out of the total pulses occurring during an integration period should be displaced by the critical frequency separation. Improvements of 6 to 10 dB in detectability due to frequency agility have been reported. The generation of frequency agile transmissions is not difficult in a coherent amplifier type of transmitter, as shown in Figure 16. However, in a magnetron oscillator type of transmitter, the local oscillator must be made to follow the transmitted frequency, a problem that requires somewhat complex circuitry and wideband local oscillators, depending upon the degree of frequency agility employed.

Agility in the radiated polarization of the transmitted signal is also of concern in achieving optimum detection performance and is receiv-



(a) NON-COHERENT INTEGRATION



(b) COHERENT INTEGRATION

Figure 15

Coherent and noncoherent integration.

ing some attention in developmental systems although the improvement in performance due to polarization agility is reported to be less than 3 dB.

Phase Coherency

In detecting a target, radar does not depend on just a single returned pulse to provide an indication but depends on the integration or the addition of a number of pulses that are reflected from a target. In a conventional pulse radar, the received pulses are integrated by using a long-persistent-screen cathode ray tube and the human eye. In this case, the cathode ray tube acts as a storage device for the target information. In more advanced radar, information data is not always displayed on a CRT and another kind of storage device is used to integrate the information. Integration of signals can be performed either at the IF frequency (before the second detector) or at the video frequency (after the second detector). If the integration is performed at the IF frequency, it is called predetection integration or coherent integration; integration at the video frequencies is called postdetection or noncoherent integration. See Figure 15.

Since the second detector's output is a rectified envelope of the pulse, phase information is lost and integration can only be performed on the video pulse. In addition, the second detector can introduce some noise because of inherent non-linearities, reducing the integration efficiency. The coherent integrator preserves the phase information and does not suffer the second detector's loss in signal-to-noise ratio, making it a much better integrator. The coherent integrator requires preserving the phase of the received signal from pulse to pulse which in turn requires a coherent reference signal to maintain the phase relationship between the transmitted and received signals. All other things being equal, a coherent detection system can obtain longer detection ranges than a noncoherent

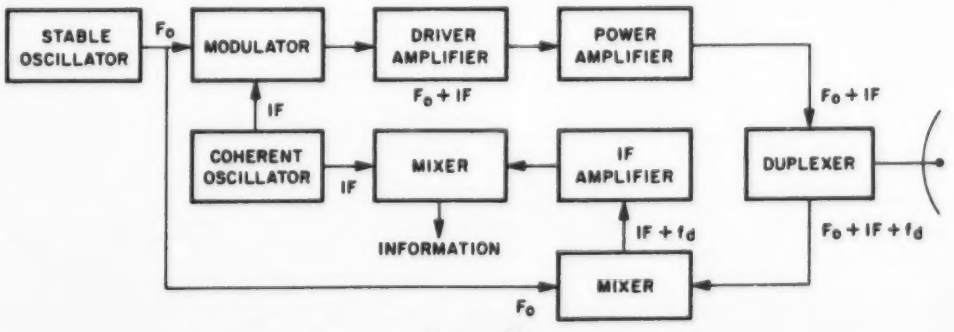


Figure 16

Coherent radar system block diagram.

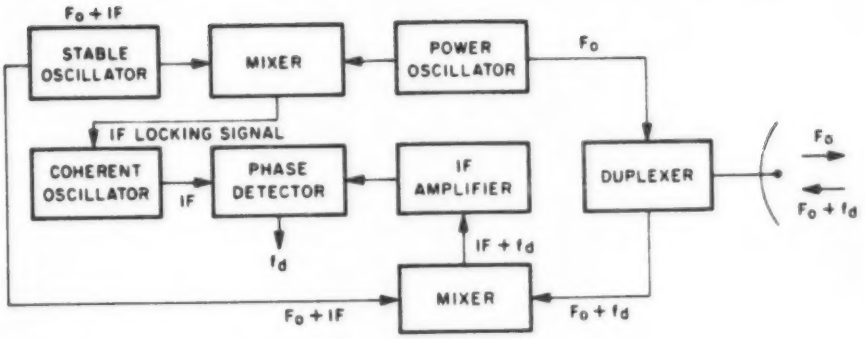


Figure 17

Coherent-on-receive radar block diagram.

detection system and also affords the measurement of doppler frequencies, resulting in increased emphasis in the development of coherent systems. A typical coherent system is shown in Figure 16.

Systems may incorporate a coherent detection system on a single pulse basis to measure doppler information. A system using a magnetron transmitter (whose starting phase can be different on each transmitted pulse) can be adapted to provide doppler information by phase locking a coherent reference signal with each transmitted pulse as shown in Figure 17.

MTI, AMTI, Delay Line Canceller

If an application, such as an air traffic control radar, is interested only in moving targets, fixed targets can be effectively eliminated by a technique known as MTI, or Moving Target Indication. This technique takes advantage of the effect that the relative motion of a target has on the reflected radar signal. The fixed targets are reflected at the same frequency as the transmitted signal while the moving target reflections experience the doppler frequency shift effect. The fixed targets can be regarded as DC signal components and the moving targets as AC signal components and if an interpulse period of information can be delayed a 1/PRF length in time and inverted in polarity, then the fixed-target components can be made to cancel out, leaving the moving target components to subtract or add at their respective doppler rates, depending on phase. Figure 18 shows the process of extracting moving target information using a delay line cancellation technique.

In a radar employing an MTI detection system, the range information is unambiguous within the interpulse period. However, it can be seen that, in a pulse radar, some velocity information becomes ambiguous, since any target velocities with doppler frequencies corresponding to the pulse recurrence frequency and the multiples of the pulse recurrence frequency (see Figure 1) will not be "seen" by the receiver and are known as "blind speeds". This may be better explained by saying that any doppler shift at the PRF frequency or at multiples of the PRF frequency will not be discernible from the returned signals of the transmitted spectral PRF lines. Thus, doppler shifts that can be measured must lie between the PRF spectral lines. The number of blind speeds of an MTI radar can be reduced by employing different or staggered PRFs on a time-sharing basis.

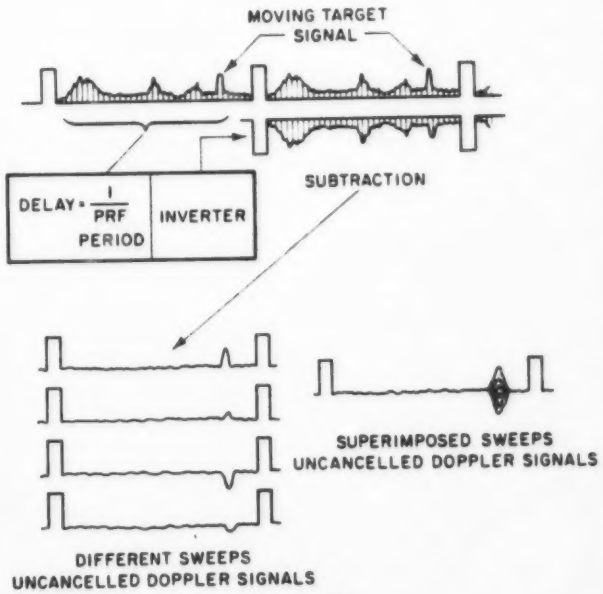


Figure 18

Delay line type of moving target indication.

An MTI function in an airborne radar (AMTI) is somewhat more complex than in a fixed-location radar system, since in an airborne radar all targets have some doppler frequency shift. Thus, a doppler "bias" frequency must be applied to subtract out the vehicle's velocity component so cancellation can occur in the same manner as fixed targets and clutter are cancelled in ground-based radars. The problem gets more complex when the applied doppler correction frequency must be changed when the antenna scans off the boresight position, since the doppler frequency shift in the return signal varies with the direction the antenna points.

Range-Gated MTI

More recently, radar equipment data processing methods are taking advantage of the digital data processing techniques that have been rapidly advanced by the computer industry. Because of the doppler effect, moving targets reflect a radar signal with a small frequency shift relating to the relative radial velocity of the target to the radar. Therefore, the existence of a doppler frequency shift in a returned signal can be used as a digital difference between stationary and moving targets. The doppler frequency shift is detected by standard frequency-domain detection methods and is used to apply a video signal to an indicator. While the "moving target" signal is detected in the frequency domain, the time relationship to establish the range of the target is accomplished by sampling small segments of range by sequential time gating of the receiver. In this way, a signal that is detected with a doppler frequency shift can be displayed on an indicator at a range position corresponding to the time of the "on" gate of the receiver during which the signal is received. All signals that are received from stationary targets can still be detected with standard amplitude detection methods and viewed on a separate indicator or processed as separate video signals. Most importantly, stationary target signals do not appear in the output of the frequency domain detector. Thus the ratio between moving and stationary signals is improved substantially over a conventional delay line cancellation technique. The range-gated MTI system requires good frequency and phase stability during each PRF period to prevent the generation of false doppler signals that would give rise to false moving targets or raise the level of the video threshold. Accordingly, range-gated MTI systems use very stable microwave amplifiers to achieve coherent operation with good continuous phase relationship during the PRF period.

Pulse-Doppler Radar Systems

A pulse-doppler radar system and a pulse radar system with MTI operation are quite similar; i.e., both systems are trying to obtain both range and velocity information. The real difference is that the pulse-doppler radar extracts unambiguous velocity within finite limits at the cost of ambiguous range information. The MTI radar has been described as extracting unambiguous range information within finite limits at the cost of ambiguous velocity information. The pulse doppler radar is designed to extract doppler information for purposes of finding and tracking a target in a high clutter environment and during high closing rate situations. An important feature of a pulse doppler system is its capability of detecting the presence of a frequency rather than detecting a signal above a determined amplitude level. This feature makes it an inherently automatic device that can detect signals down to thermal noise levels. Pulse doppler radars are characterized by high pulse recurrence frequencies, usually in the 10 kHz to 300 kHz range, and, as in the case of the MTI radar, use a technique of changing the PRF to minimize ambiguities, in this case, range. Figure 19 shows a typical example of switching the PRF to measure the "second time around" signals and to identify them with the right transmitted pulse.

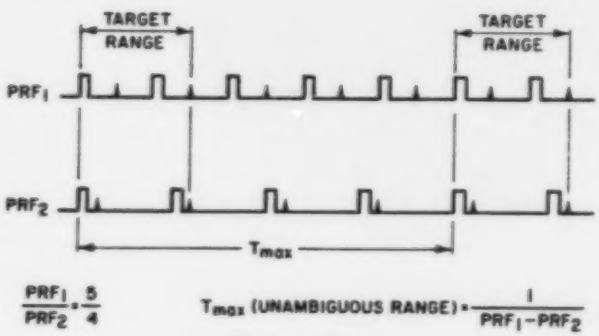


Figure 19
PRF switching.

The PRFs that are used have a numerical relationship, such as 5 and 4 or 18 and 19, and will be dependent upon the unambiguous velocity limits to be handled (to avoid blind speeds) and

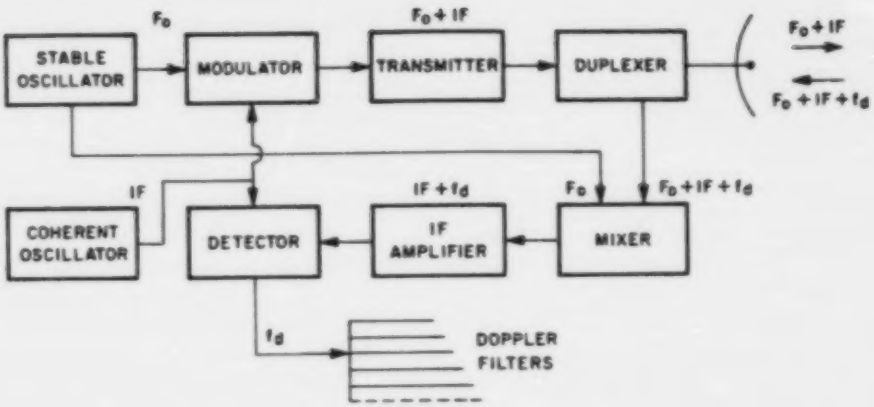


Figure 20

Pulse doppler radar block diagram.

the unambiguous range interval desired. Figure 19 shows the relationship of two PRFs and the maximum unambiguous range interval. A typical block diagram of a pulse doppler system is shown in Figure 20.

Monopulse Radar Systems

A monopulse radar system is a tracking radar that derives all its tracking error information from a single pulse. In addition, new and independent error information is generated with each new pulse.

The basic principle of monopulse radar is that of combining the RF circuits of two antennas to simultaneously obtain both sum and difference signals. The antenna patterns overlap as shown in Figure 21a. The sum of received signals of the two antenna patterns are shown in Figure 21b and the difference of the received signals in Figure 21c.

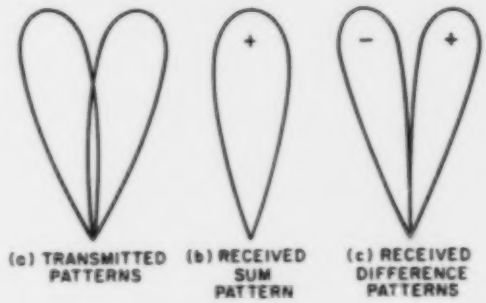


Figure 21

Monopulse radar antenna patterns.

Physically, two antennas are not necessary since the "arithmetic" can be accomplished with a single parabolic reflector and two radiators, or "feeds", displaced from the focal point of the antenna.

The sum pattern is used for transmission of the pulse while both the sum and difference patterns are used to receive the pulse. Figure 22 shows a block diagram of a single-coordinate system.

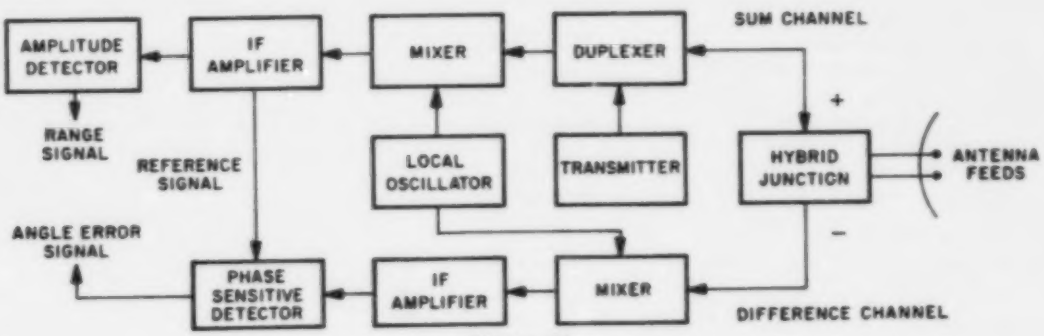


Figure 22

Amplitude-comparison monopulse radar block diagram.

The difference pattern signal provides the magnitude of the angle error while the sum pattern signal provides the reference to extract the sign of the error signal. The sum signal also provides a means of extracting the radar range measurement as in a conventional pulse radar. If two-coordinate information is desired (azimuth and elevation), then four antenna feeds can be used to provide the sum and difference patterns in quadrature.

Synthetic Aperture Radar Systems

A synthetic aperture radar is one that employs a means of obtaining increased azimuth or angular resolution by using the technique of a synthetic aperture antenna. To date, the main application of these radars are in Side Looking Radars, which are used for high-resolution radar mapping. The synthetic aperture antenna is the name given to a method of transmitting and receiving where the motion of the vehicle traveling in a straight line effectively creates a linear array of antenna elements as the vehicle moves through a specified time period (see Figure 23). The target information received in this time period is stored and later processed to achieve an increase in angular resolution.

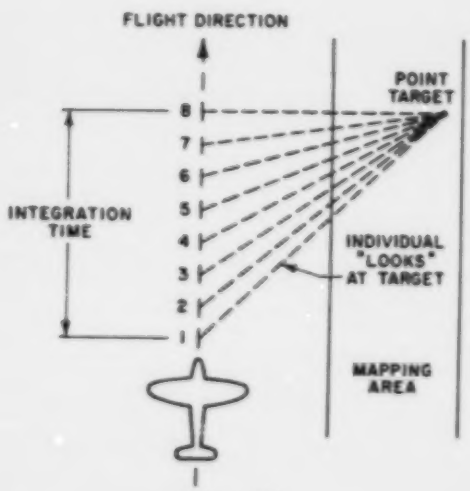


Figure 23

Synthetic aperture antenna.

The doppler frequencies received from a point-target return signal will decrease as the vehicle approaches a perpendicular range position (Figure 23, Position 8) where the doppler signal will be zero. The doppler history of the point target as shown in Figure 24 corresponds to the positions indicated in Figure 23.

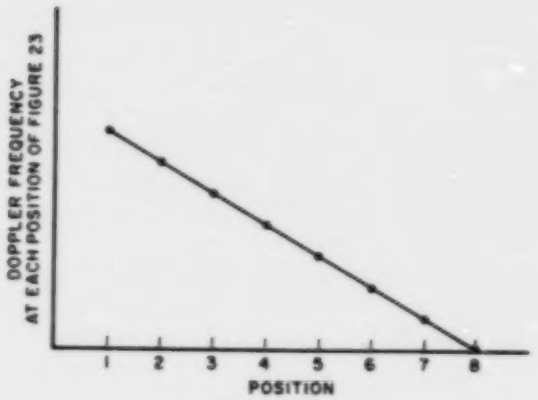


Figure 24

Doppler frequency history of a point target.

The doppler histories of the target area are recorded on signal film by a photographic process as shown in Figure 25.

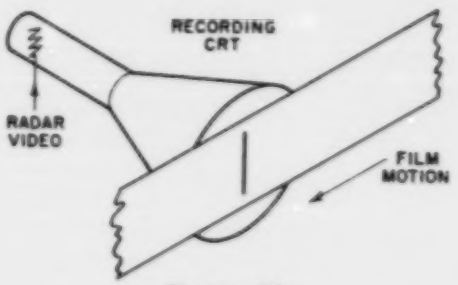


Figure 25

Recording of doppler signal on raw data film.

A line is scanned on the film at the PRF rate. The vertical position then corresponds to range. The signal strength of the targets provides density modulation of the film (exposure). A simple drawing of the doppler modulation and how it is recorded on film is shown in Figure 26

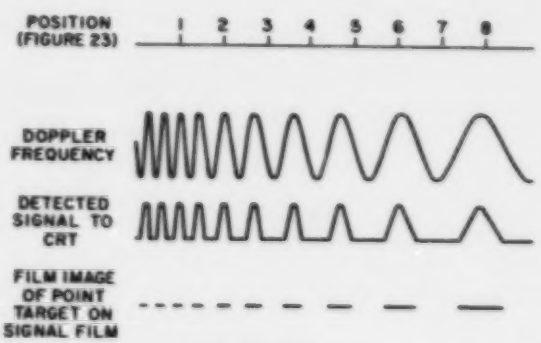


Figure 26

Doppler signal modulation of signal film.

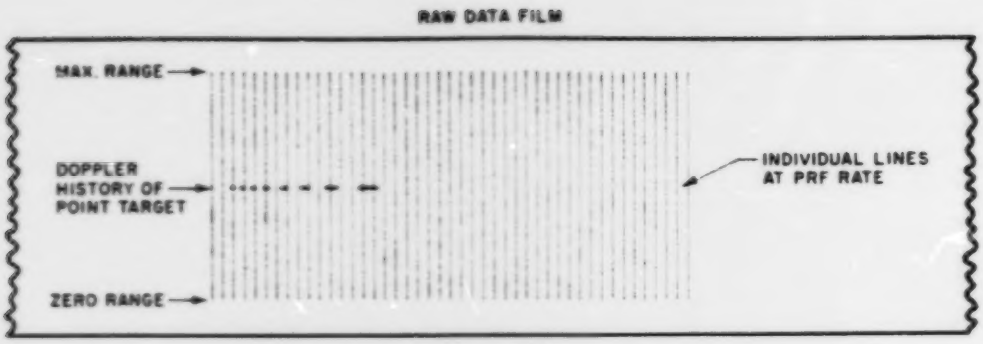


Figure 27

Synthetic aperture antenna radar signal film.

corresponding to the doppler history of Figure 24. The signal film then stores a doppler history of each point target at its particular range as shown in Figure 27. The signal film is then processed in an optical processor to produce a radar image film, which in turn is used as a negative film to produce a photographic image, a radar map picture.

Each doppler history performs as an individual Fresnel lens and when the signal film is illuminated by a coherent light source, such as a laser, each point target is focused on the image film as a point as illustrated in Figure 28. The entire radar map is made up of the integration of all the point targets and the angular resolution is then a function of the resolution capability of each point target. Of significance is the ability of the radar to maintain optimum resolution that is independent of range, referred to as having a "focused" antenna.

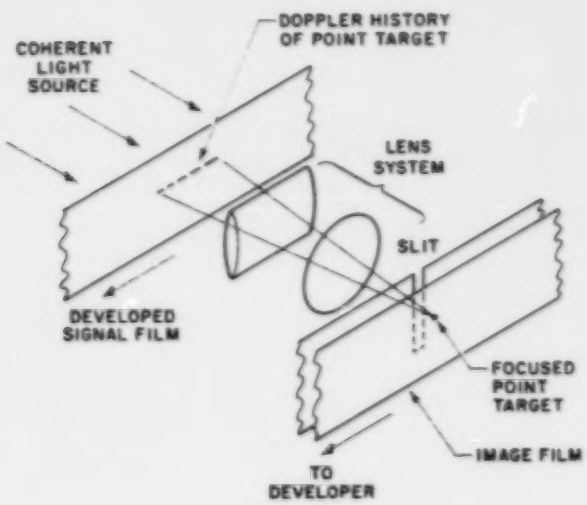


Figure 28

Fresnel lens effect on focusing point targets.

The range resolution of the Synthetic Aperture Radar is achieved by pulse compression techniques. Thus the radar employs the ultimate in range and angular measurement techniques and provides the best radar resolution achievable in the present state of the art.

The present disadvantage of the synthetic array radar is the time required to obtain the final radar image. It is not a "real-time" radar, or one where the radar image is instantly available as in standard radar systems. Presently, signal film is either physically returned to a processing facility or the radar data is transmitted to a processing facility which then produces an image film and radar map pictures.

The technology of digitally processing radar data is being applied to synthetic aperture radars and it appears that in the near future these radars may become real-time systems if devices for storing sufficient data become available. A total storage capacity of the order of 10^7 bits is required to handle the amount of information data that must be processed. There is considerable optimism in the industry that many future radars, in addition to side looking radar, will employ the synthetic array techniques to achieve high resolution radar images.

ANTENNAS

From the radar equation, it can be seen that the detected radar range depends upon the antenna's gain, aperture, and efficiency. Other system factors that enter into antenna design considerations are scanning rate, stabilization, power-handling capability, size, shape, etc.

(a) CONVENTIONAL FEED AT FOCAL POINT (b) CASSEGRAIN FEED

Figure 29
Parabolic antennas.

Parabolic Reflectors

Most radars use a parabolic reflector of some kind, fed either at the focal point (Figure 29a) or at the surface of the reflector in a Cassegrain configuration (Figure 29b).

Parabolic reflector antenna surfaces are often modified to obtain wider field patterns for greater search areas, especially in airborne radar where ground illumination at all ranges is desired. One type of a modified parabolic reflector, often used, is called a "cosecant squared" reflector. It provides a radiated field at both close and far ranges.

Phased Arrays

The phased array antenna consists of many individual radiating elements that are suitably spaced with respect to one another. By controlling the phase and amplitude of the signals applied to each element, desired radiation patterns can be obtained from the combined action of all elements. If all elements are spaced in a straight line, it is called a linear array. If the elements are arranged in two dimensions in a plane, it is called a planar array. If each element has a separate transmitter tube it is called an active array.

Reflectors now being developed contain a mosaic of many phase shifters that are computer programmed to achieve an electronic control of the phase of the reflective surface, affording a high scan rate over a limited angle without mechanical movement of the antenna. Antenna arrays are also produced using many individual phase shifters that are all illuminated by one large power source from one antenna feed. The array is essentially a microwave lens that electronically controls the beam by controlling each individual phase shifter. Antenna "dithering" is another technique used to reduce clutter. An electronically-controlled antenna is obviously well suited to antenna dithering applications.

Phased array antennas produce many kinds of beam shapes, including fan and pencil beams. A single phased array may be used to scan elevation electronically, while scanning the azimuth direction mechanically. Four fixed arrays can be made to scan electronically in all directions; i.e., a hemispherical scan. Hence, many combinations of electronic and mechanical scanning schemes are possible and are used accordingly to best fit the application. The size, weight, and cost of phased array antennas generally make them better suited to ground based or shipboard systems and are usually used with lower frequency radars.

MICROWAVE TUBES USED IN RADAR SYSTEMS

Early radar systems operated at low frequencies because electron tubes were not available for operation at higher frequencies. The density-modulated triodes and tetrodes used in commercial radio and communications transmitters were the only available high power tubes until velocity modulated microwave tubes were invented and produced.

The Magnetron was the first practical high-power microwave oscillator produced in large quantities and it was the principle means of providing high power microwave pulses for radar systems until microwave amplifier tubes became available. This device is a velocity modulated crossed-field oscillator (the magnetic focusing field is perpendicular to the electron beam) and is used in noncoherent radar systems. It is not used as a coherent power source, since each pulse of power has a different phase relationship to other pulses. It can only be used in a coherent system, such as a coherent-on-receive system shown in Figure 17, where the local oscillator must be phase locked to the magnetron signal on every pulse.

Magnetrons provide power at kilowatt and megawatt levels and are very efficient devices (the output power is high compared to the input power it needs to operate). They are still used in many radar systems that (1) do not require coherent detection techniques, or (2) are designed for economy and limited performance. Commercial airborne weather radars, small boat radars, and terrain following radars are examples of magnetron type radars.

The invention of the Klystron by the Varian brothers was the initial application of velocity modulating an electron beam in a linear device (straight line format). The first production klystrons were reflex klystron oscillators and were used as local oscillators in radars. These klystrons provided output power in the tens of milliwatts. Although reflex klystrons are still being used as local oscillators, they are gradually being replaced in new systems by solid-state oscillators of various types, including Multipliers, Gunn-effect diode oscillators, Avalanche diode oscillators, etc.

Klystron amplifier tubes are linear, high-gain devices (the magnetic focusing field is parallel with the beam and the tubes have a straight line format). Their existence provides an easy means for maintaining a continual phase relationship between the transmitter and local oscillator. Klystron amplifiers provide output levels from watts to megawatts and are limited in bandwidth to a few percent of the operating frequency.

Another kind of microwave tube, the Traveling Wave Tube, also utilizes the velocity modulation principle. Unlike the klystron amplifier that employs narrow band resonant cavities to interact with the electron beam, the traveling wave tube uses a wide band interaction circuit, called a slow wave structure, to provide wide bandwidth amplification. Traveling wave tubes produce output levels from milliwatts to megawatts. Along with providing output power for radars, special traveling-wave tubes are designed for receiver pre-amplifier applications, where low-noise-figure amplifiers are used to increase radar receiver sensitivity. The technology of traveling wave tubes is also used to provide Backward Wave Oscillators for wide electronic bandwidth signal generation. Hybrid tubes using both klystron and traveling wave tube technology are produced for wide bandwidth high power applications and are called Twystron® Amplifiers.

As the linear beam tube art has extended from klystrons to traveling wave tubes, so has the crossed-field tube art been extended to provide Crossed-Field Amplifiers. These amplifiers feature the good efficiency of their magnetron counterparts, have wide bandwidth, but have low gain. Crossed-field amplifiers are usually used in tandem with traveling wave tubes to provide sufficient power gain.

Figure 30 shows some types of radar systems and the kinds of microwave tubes they use.

Type of System	CW or FM-CW	Pulsed, Noncoherent	Pulsed, Noncoherent, Frequency Agile	Pulsed, Noncoherent, Narrow Bandwidth	Pulsed, Coherent, Wide Bandwidth
Transmitter	Klystron Oscillator Klystron Amplifier CW Magnetron Traveling Wave Tube Triode Oscillator	Magnetron	Dither-Tuned Magnetron Spin-Tuned Magnetron	Klystron Amplifier Tetrode Amplifier (Low frequencies)	Traveling Wave Tube Twystron® Amplifier Crossed-Field Amplifier
Local Oscillator	Transmitter signal used as L.O.	Solid-State Diode Oscillator Frequency Multiplier Reflex Klystron	Solid-State Diode Oscillator Backward Wave Oscillator Reflex Klystron	Solid-State Diode Oscillator Frequency Multiplier Reflex Klystron	Solid-State Diode Oscillator Frequency Multiplier Reflex Klystron Backward Wave Oscillator (Used as master oscillator and heterodyned for L.O. signal and/or wide-band modulation.)
Receiver Preamplifier	Not used	Usually not used	Usually not used	Low-Noise Traveling Wave Amplifier Solid-State Amplifier	Low-Noise Traveling Wave Amplifier Solid-State Amplifier

Figure 30

Microwave tube and device applications in radar systems.

RADAR RELATIONSHIPS

1. Radar Equation

$$\frac{S}{N} = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4 \overline{NF} kTB L}$$

2. S/N at Range, R

$$\frac{S}{N} = \left(\frac{R_o}{R}\right)^4$$

Ro is the range at S/N = 1

3. Antenna Gain

$$G = \frac{4\pi A}{\lambda^2}$$

A = Aperture Area

4. Antenna Beamwidth, Half Power

$$BW = \frac{51\lambda}{A}$$

5. Duty Cycle of Pulsed Radar

Du = Pulse Width x PRF

6. Average Power = Peak Power x Duty Cycle

7. Range

$$R = \frac{T_r c}{2}$$

T_r = time (round trip)
c = velocity of propagation

8. Unambiguous Range, Single PRF

$$R_u = \frac{c}{2\ PRF}$$

PRF = Pulse Recurrence Frequency

9. Unambiguous Range, Multiple PRF

$$R_u = \frac{c}{2\ (PRF_1 - PRF_2)}$$

10. Interpulse Period

$$T = \frac{1}{PRF} - \tau$$

τ = Pulse Width

11. Velocity of Propagation (velocity of light), c

c = 2.997925×10^8 meters/second
c = 186,282 statute miles/second
c = 161,875 nautical miles/second
c = 984 feet/microsecond

Time to travel one (1) nautical mile, round trip, = 12.34×10^{-6} seconds.

12. Doppler Frequency

$$F_d = \frac{2\ V_r F_o}{c}$$

V_r = Relative Velocity
F_o = Transmitted Frequency

13. Pulse Compression Ratio

Ratio = ΔF x Pulse Width

Compressed Pulse Length = $\frac{1}{\Delta F}$

Compressed Pulse Amplitude = $A\sqrt{\Delta F\ \tau}$

A is transmitted peak power of pulse.

14. Wavelength

$$\lambda = \frac{c}{F}$$

c = Velocity of Propagation
F = Frequency

15. Receiver Bandwidth

(a) Low PRF Radars

$$BW = \frac{1}{\tau}$$

(b) High PRF Radars (Pulse Doppler)

$$BW \text{ (each filter)} = \frac{B}{T_i^2}$$

B = Antenna Beamwidth,
T_i = Target Illumination Time

16. Noise Figure of an Amplifier $\overline{NF}$

$$\overline{NF} = \frac{S/N \text{ In}}{S/N \text{ Out}}$$

17. Overall Noise Figure of a Series of Amplifiers, 1, 2 and 3.

$$\overline{NF} = \overline{NF_1} + \frac{\overline{NF_2} - 1}{G_1} + \frac{\overline{NF_3} - 1}{G_1 G_2}$$

G = Amplifier Gain

18. Thermal Noise Level

$$kTB = -204 \text{ dBW/Hertz}$$
$$= -114 \text{ dBm/MHz}$$

19. Boltzman's constant

$$k = 1.38 \times 10^{-23} \text{ joule/degree}$$

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